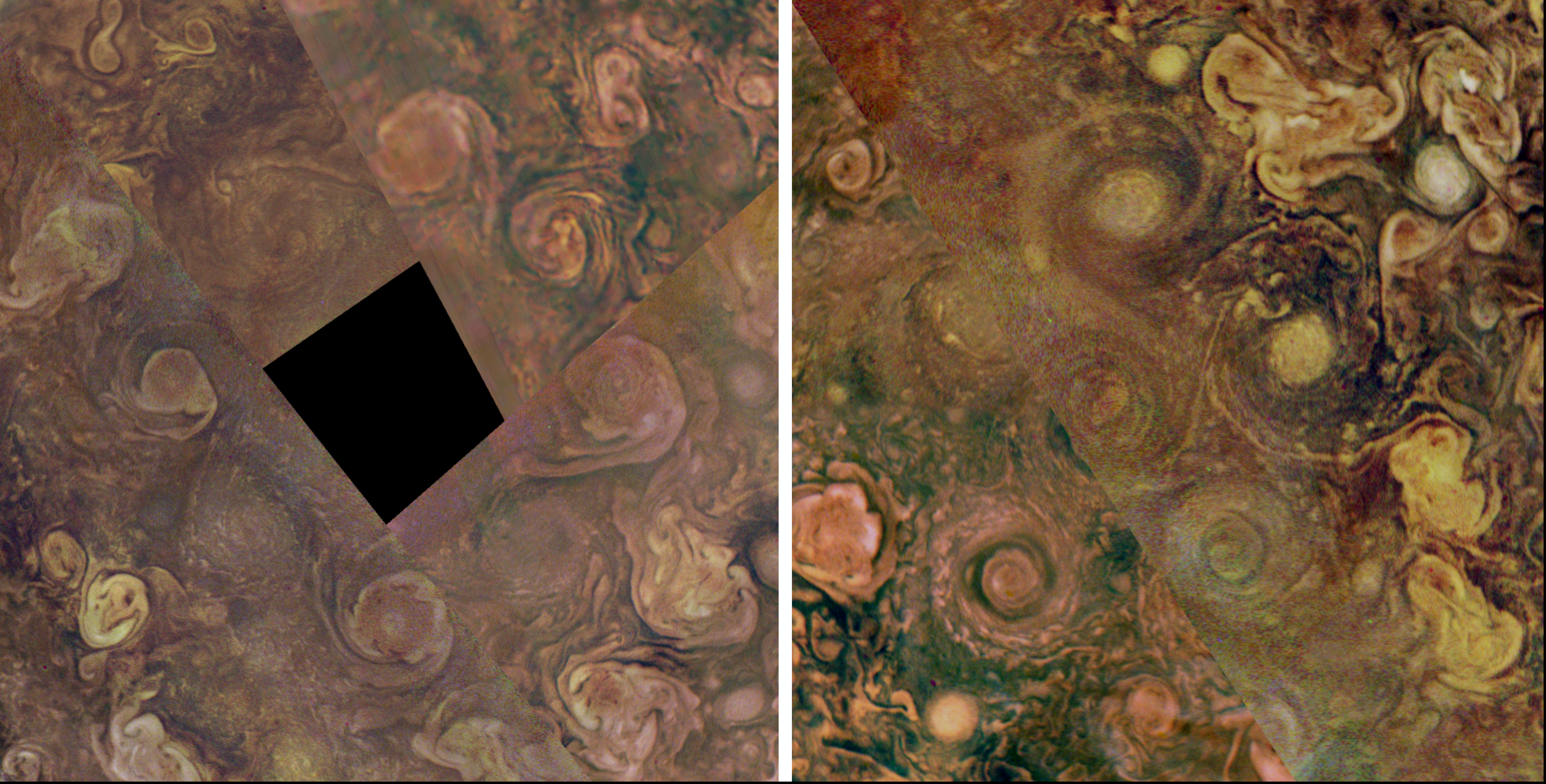


Long-term evolution of circumpolar cyclones on Jupiter’s poles with Juno

Fachreddin Tabataba-Vakili and the JunoCam team

JUNO

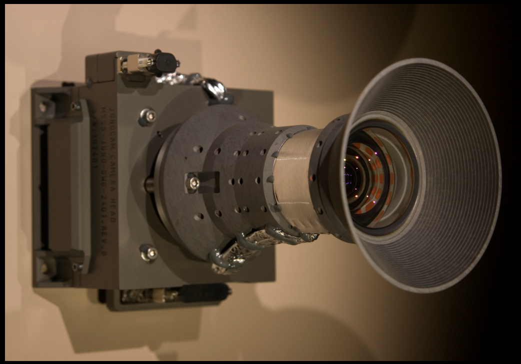
Jet Propulsion Laboratory
California Institute of Technology

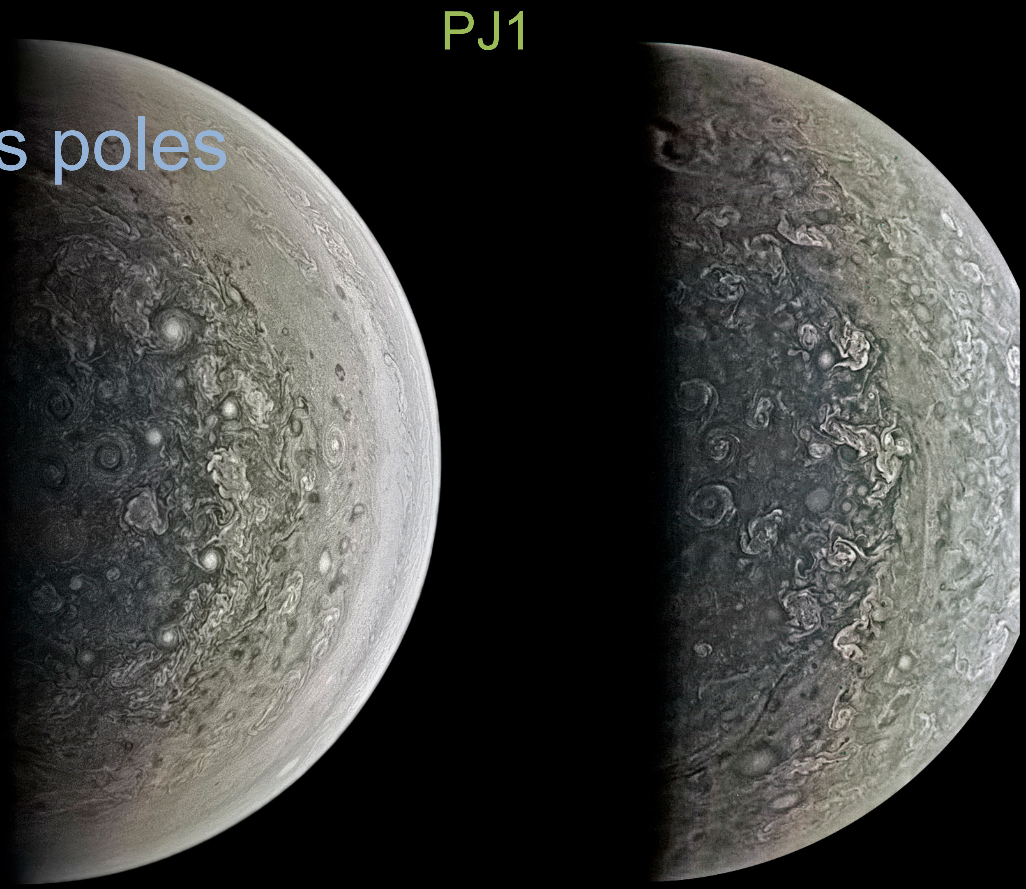
JunoCam

JunoCam is on the Juno payload to give the public an opportunity to participate in a planetary mission

Unique views of Jupiter's poles

Drove the camera design

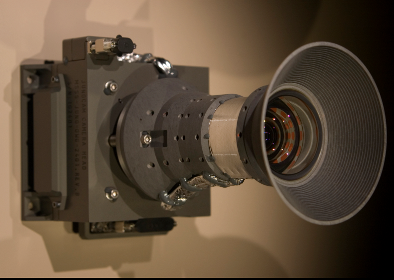




South Pole

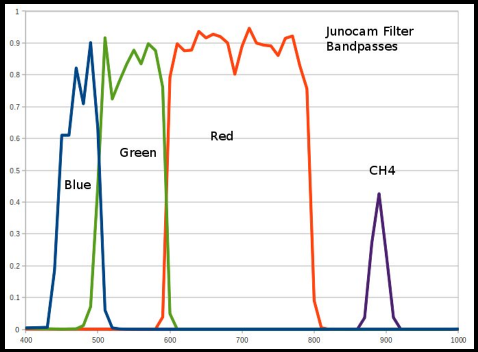
North Pole

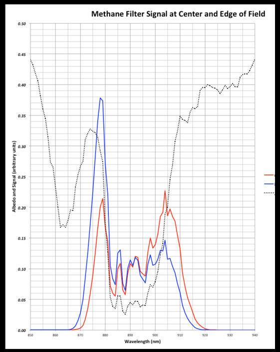
NASA / JPL / MSSS / Roman Tkachenko



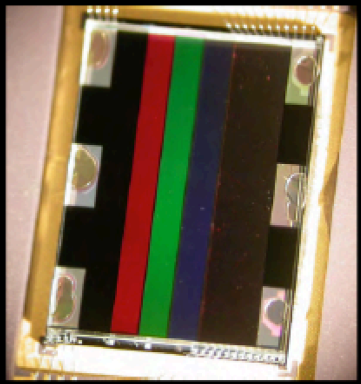
JunoCam Description

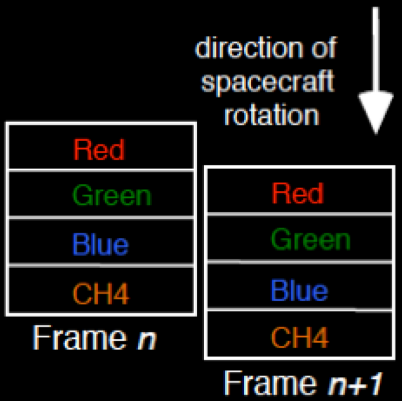
- JunoCam is a fixed-mounted, fixed field of view push-frame visible camera that images in four color bands
  - Broadband blue, green and red
  - Narrow methane band filter centered at 889 nm





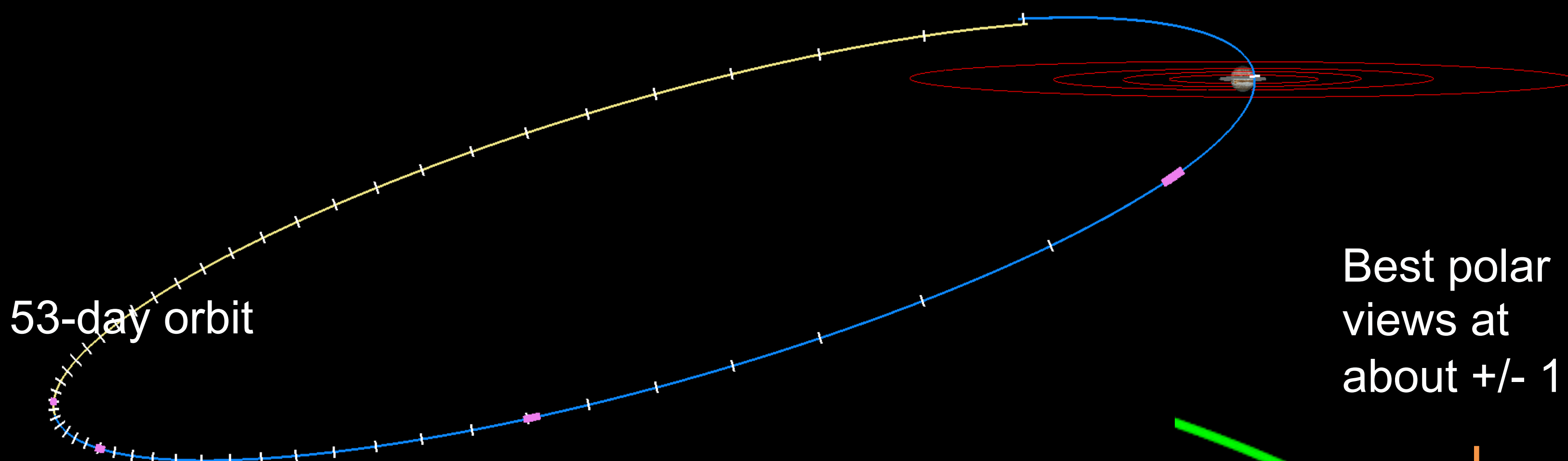
- *A JunoCam image is acquired as S/C rotation sweeps the 1600 pixel, 58° wide FOV across Jupiter*



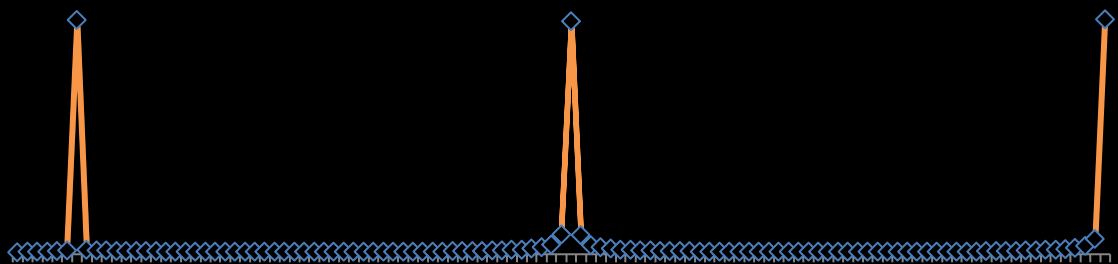


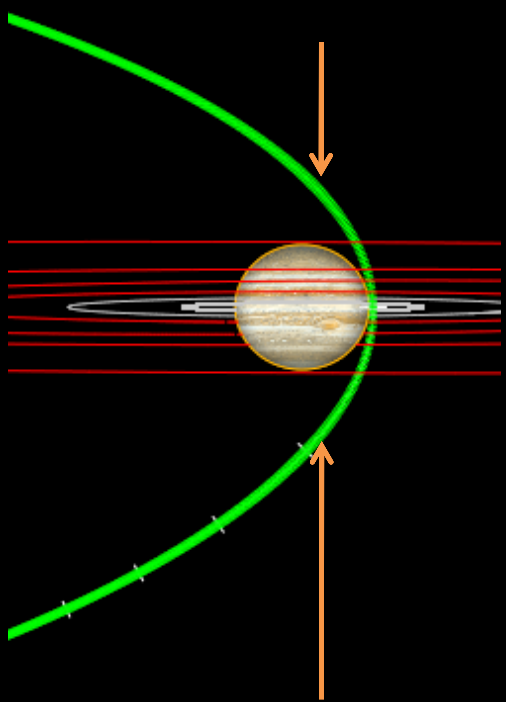
- Time-delayed integration (TDI) used to build up SNR
- Built and operated by Malin Space Science Systems

Juno's Elliptical Polar Orbit



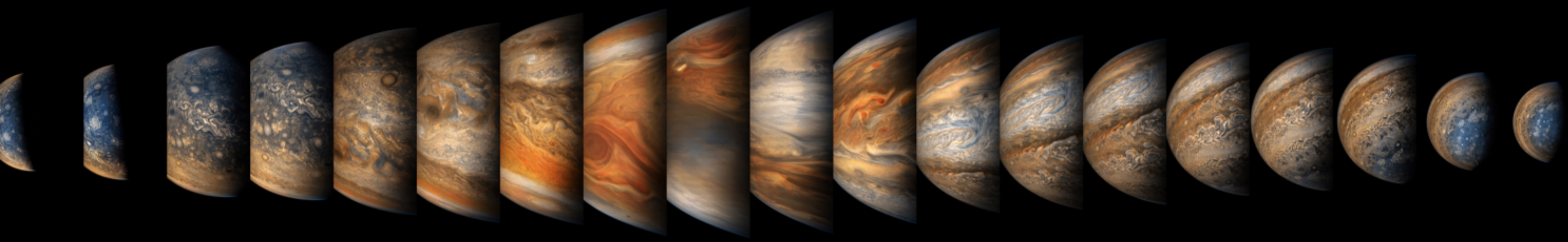
Jupiter is <50 pixels for most of Juno's orbit



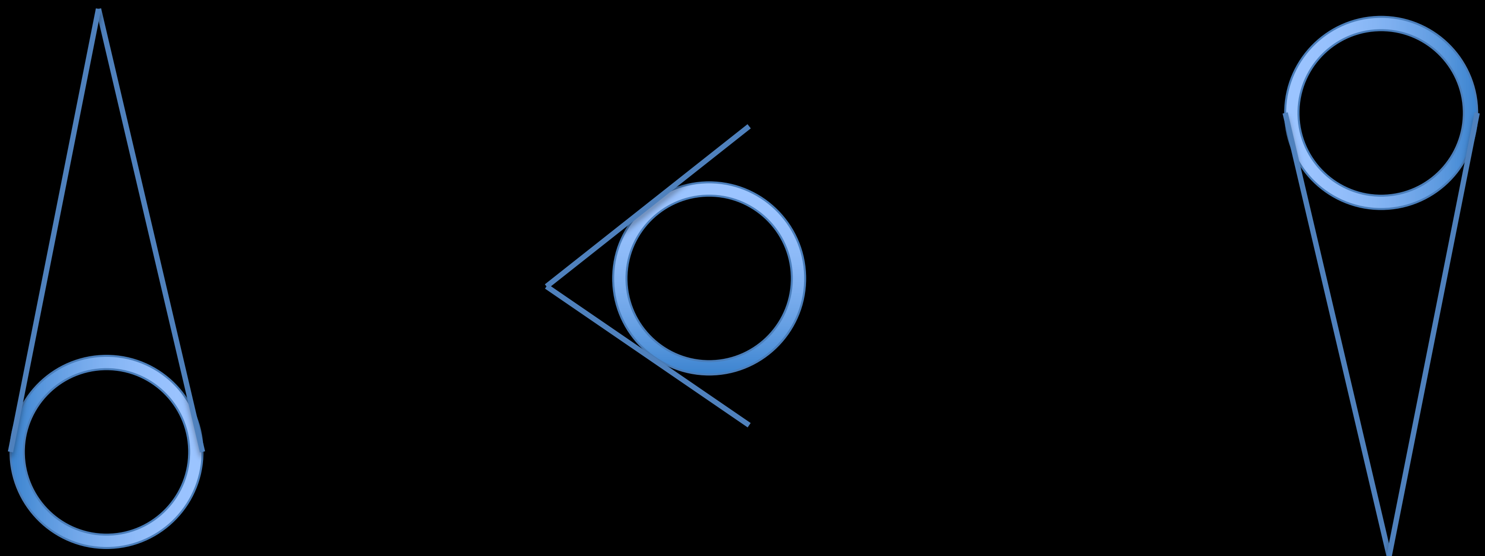


- Perijove swath begins ~1 hr before closest approach
- ~2h from north pole at minimum emission angle to south pole at minimum emission angle

PJ8 Perijove Pass



NASA / JPL / MSSS / Gerald Eichstädt / Sean Doran

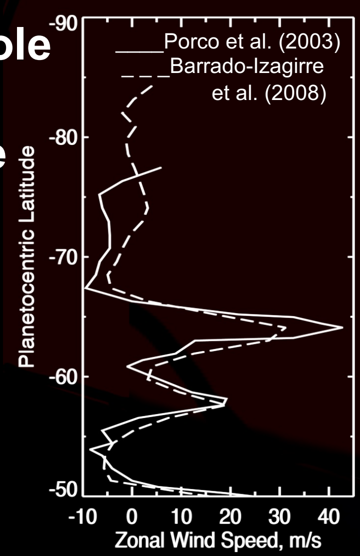


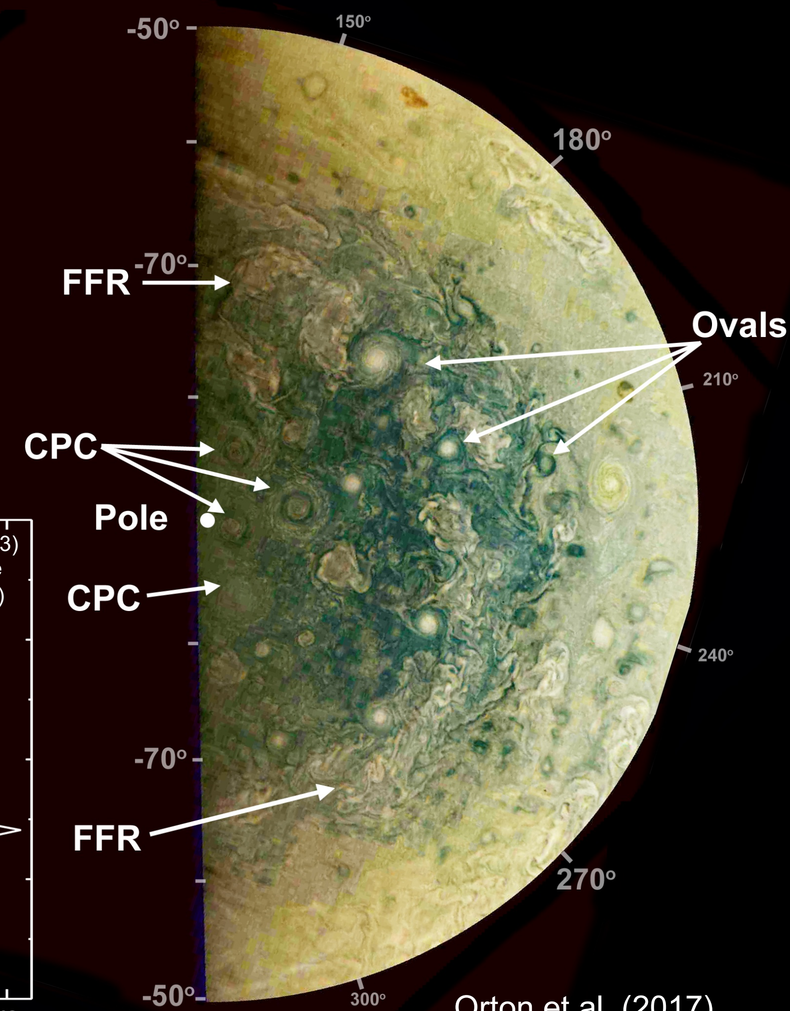
Polar Observations with Juno

JunoCam: South Pole

Perijove 1 (PJ1)

- FFR: Folded Filamentary Regions
  - Longest reaches across 10000 km
  - Colocated with eastward jet near 65°S
- Oval vortices
  - Largest is anticyclonic
- **CPC: Circum-polar Cyclones**
  - **Cyclonic vortices**
  - **Clustered around the pole**
  - **Central cyclone is slightly offset from pole**





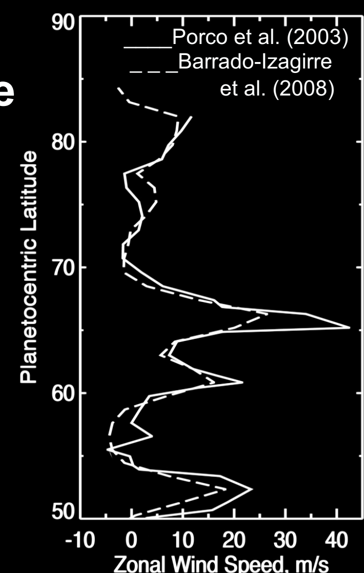
Orton et al. (2017)

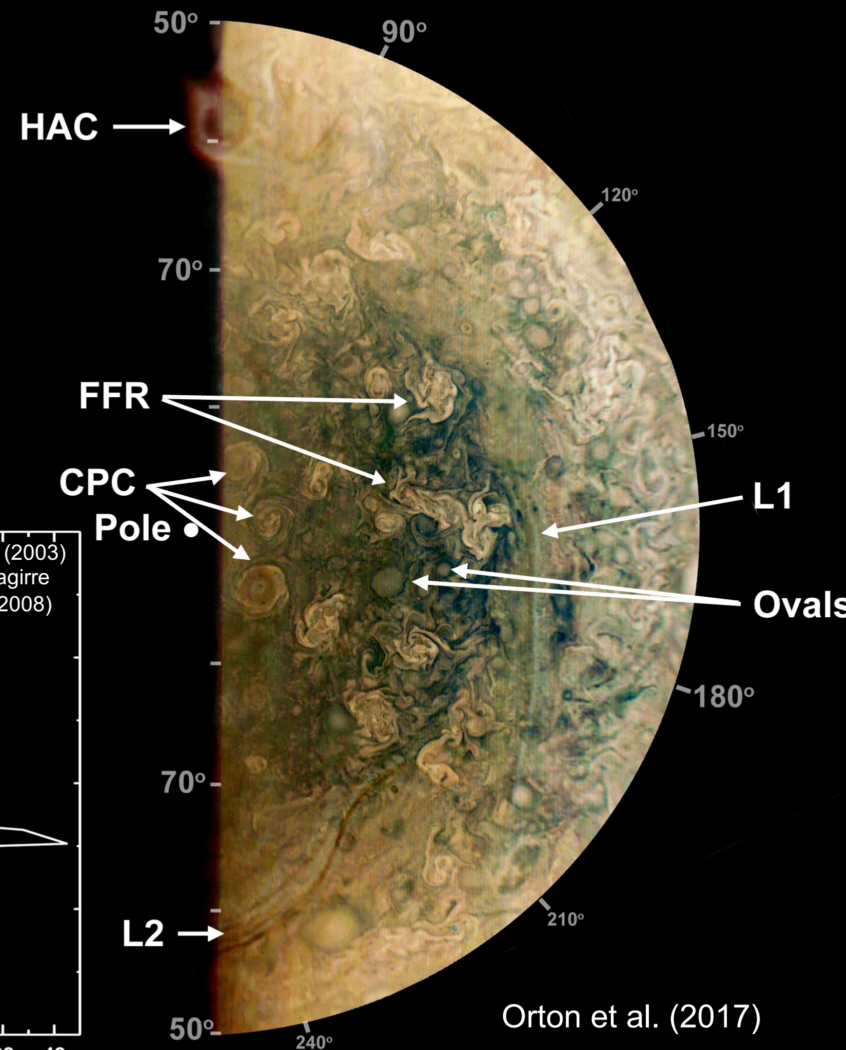
Polar Observations with Juno

JunoCam: North Pole

Perijove 1 (PJ1)

- FFR: Folded Filamentary Regions
  - Longest reaches across 4000-7000km
- Oval vortices
  - Largest is anticyclonic
- **CPC: Circum-polar Cyclones**
  - **Cyclonic vortices**
  - **Clustered around the pole**
  - **Central cyclone is slightly offset from pole**



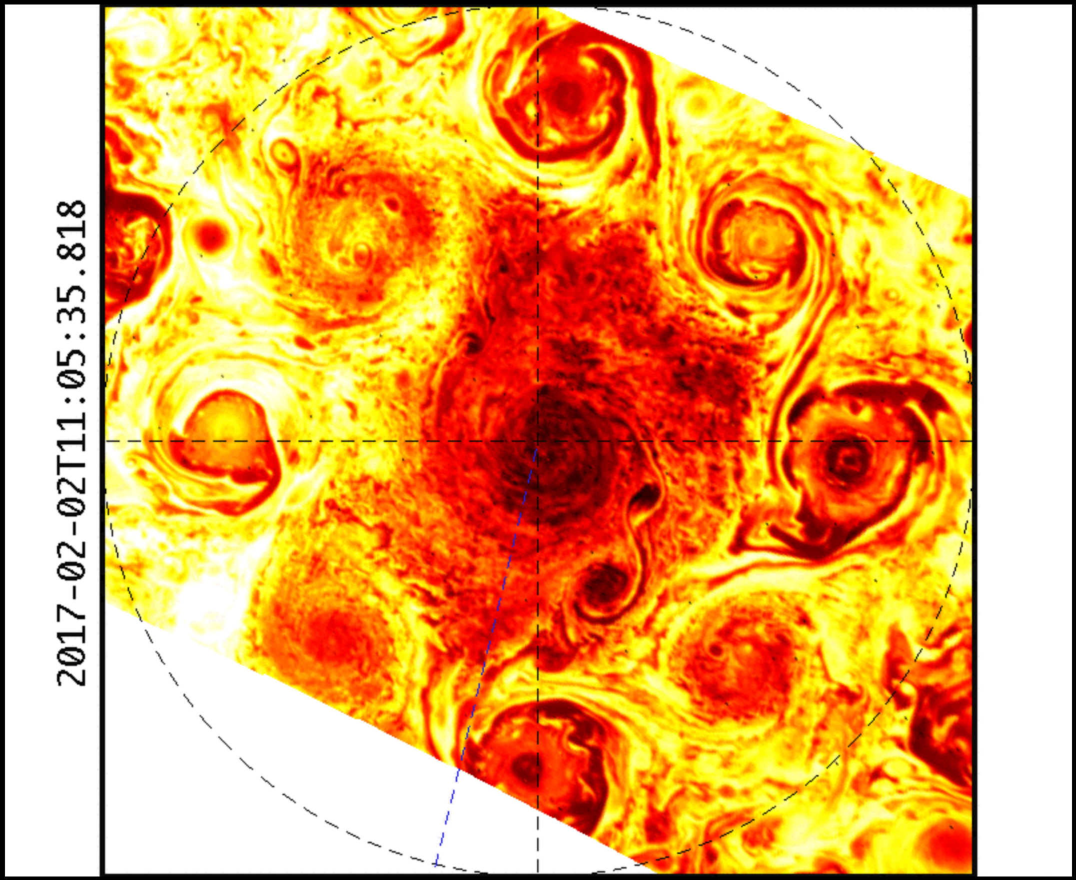


Orton et al. (2017)

Polar Observations with Juno

JIRAM (Jovian Infrared Auroral Mapper)

- Perijove 4
- North pole

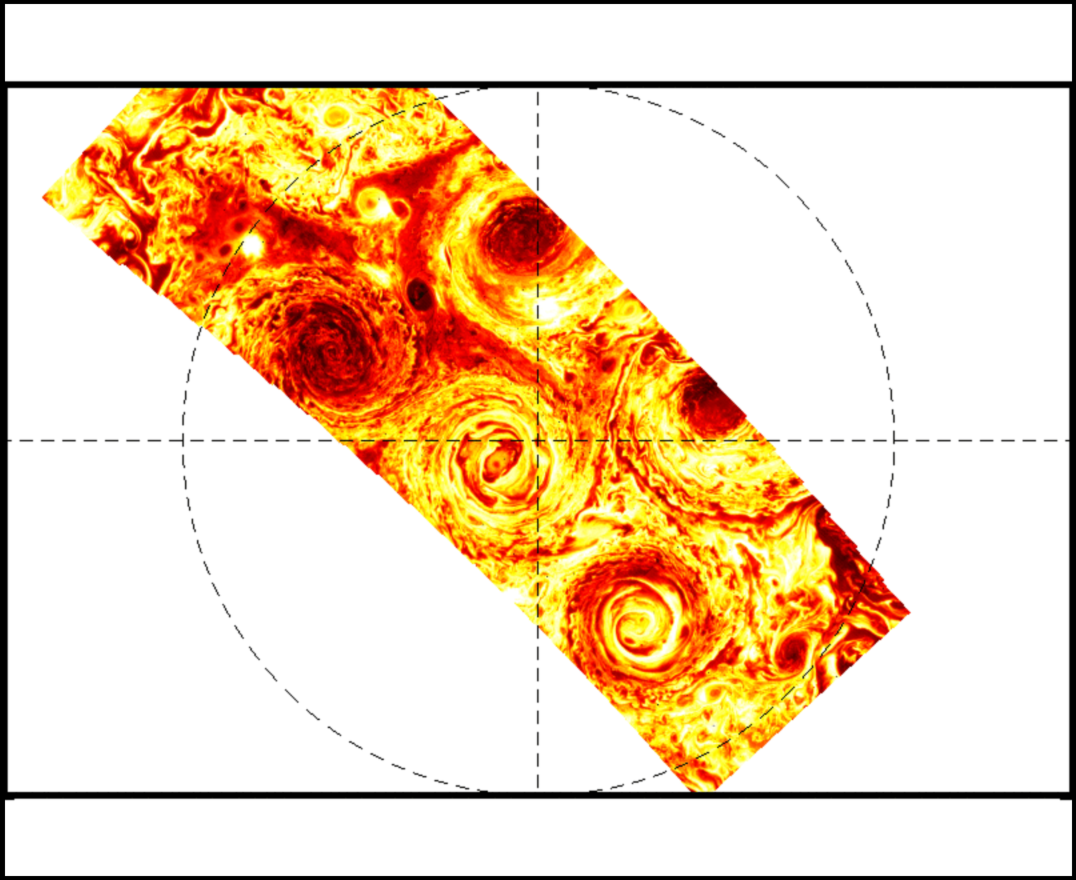


Adriani et al. 2018

Polar Observations with Juno

JIRAM (Jovian Infrared Auroral Mapper)

- Perijove 4
- South pole

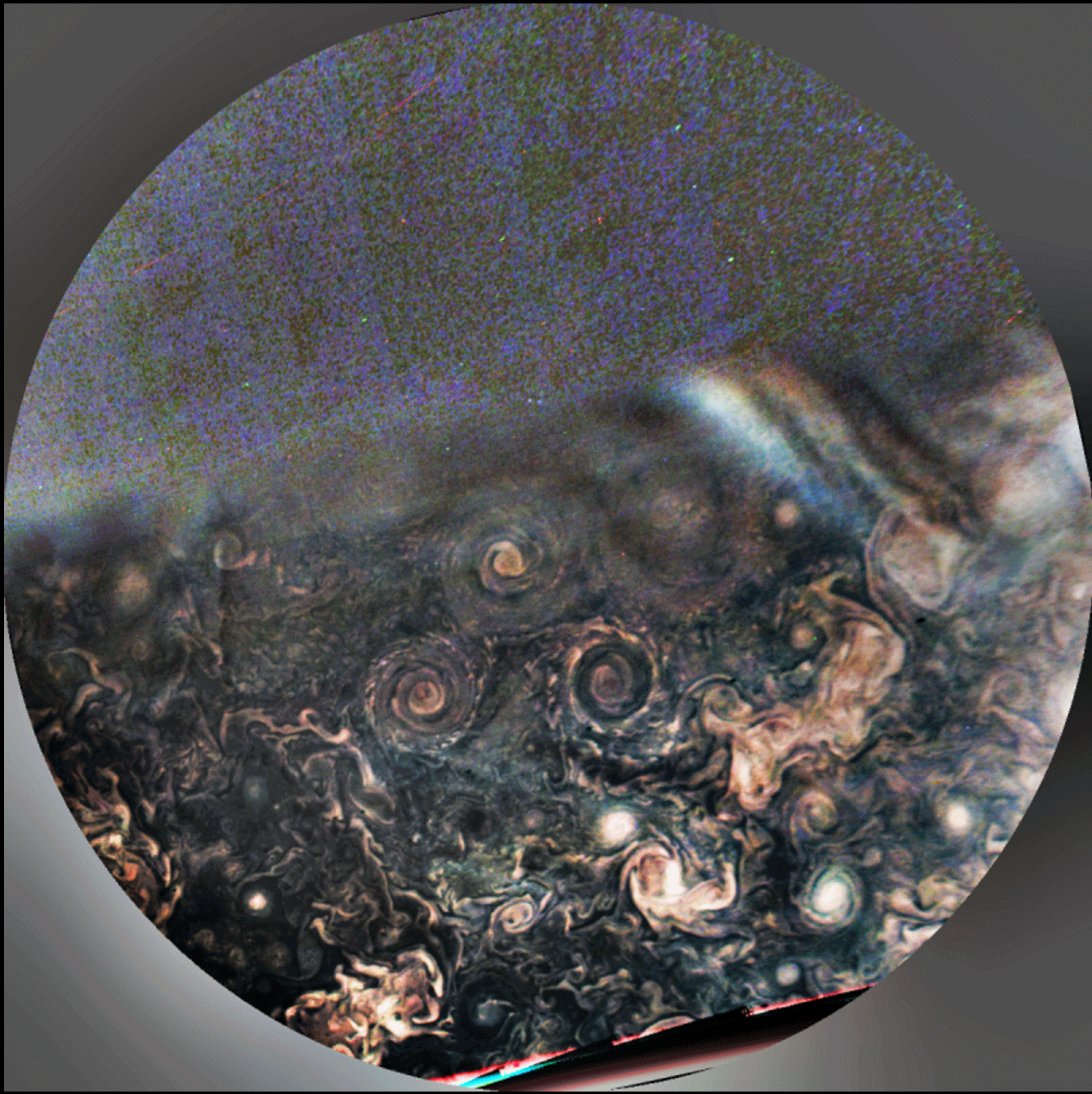


Adriani et al. 2018

Polar Observations with Juno

South Pole: Animations

- Perijove 5

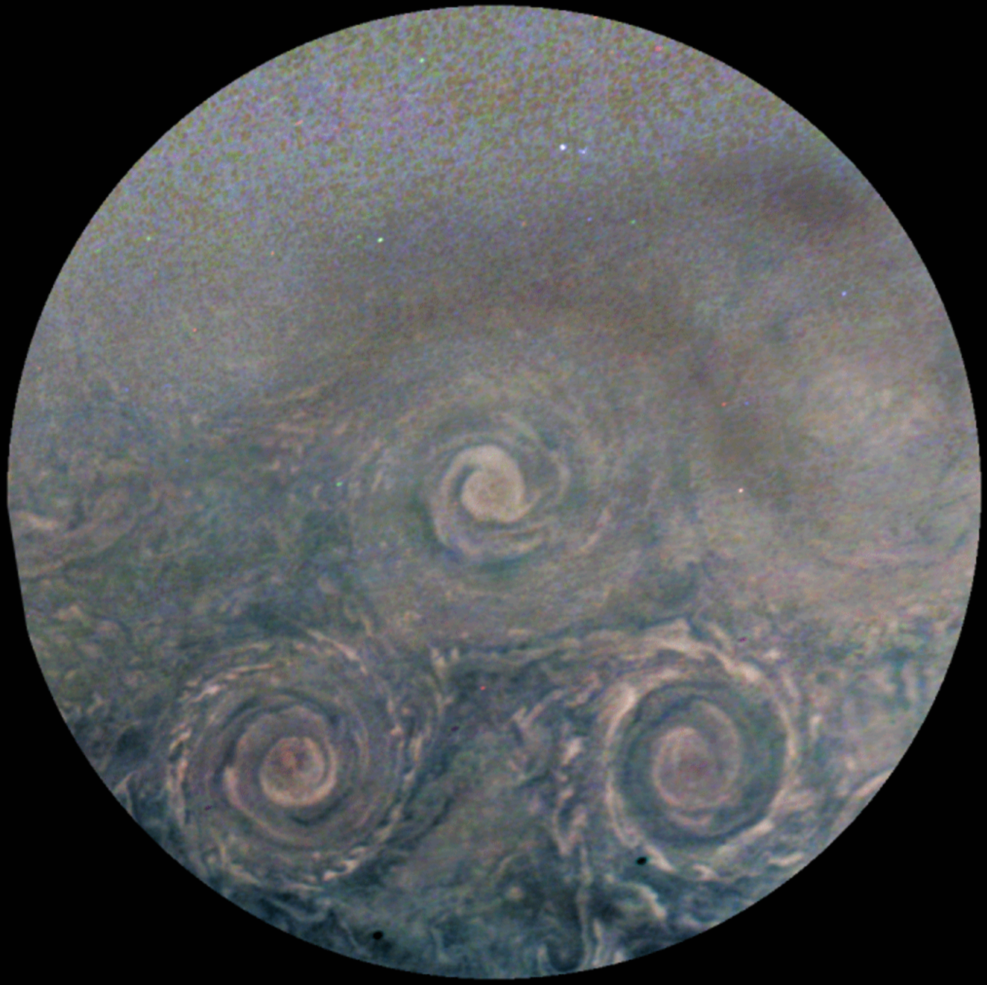


NASA / SwRI / MSSS / Gerald Eichstädt

Polar Observations with Juno

South Pole: Animations

- Perijove 5

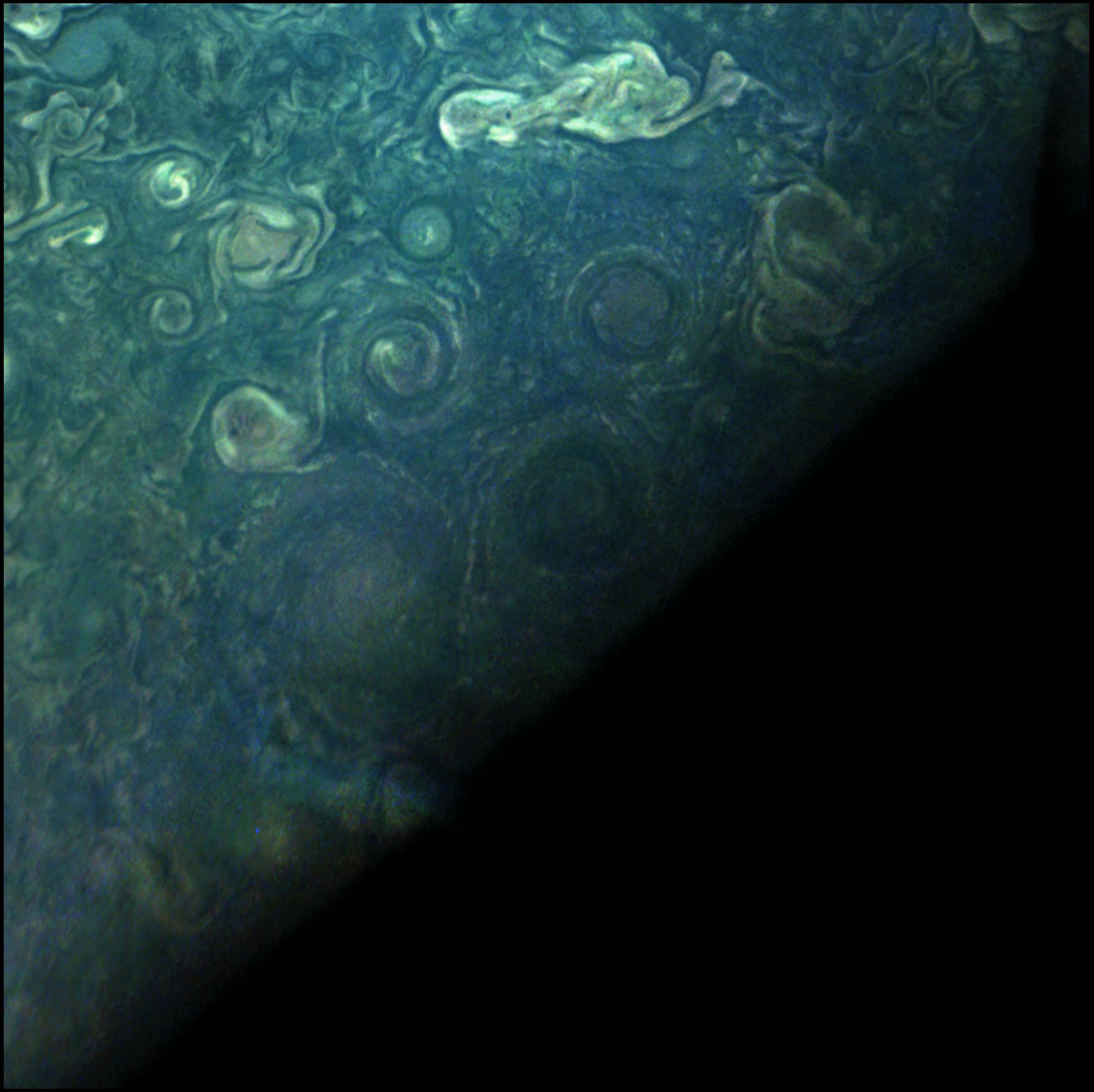


NASA / SwRI / MSSS / Gerald Eichstädt

Polar Observations with Juno

South Pole: Animations

- Perijove 9

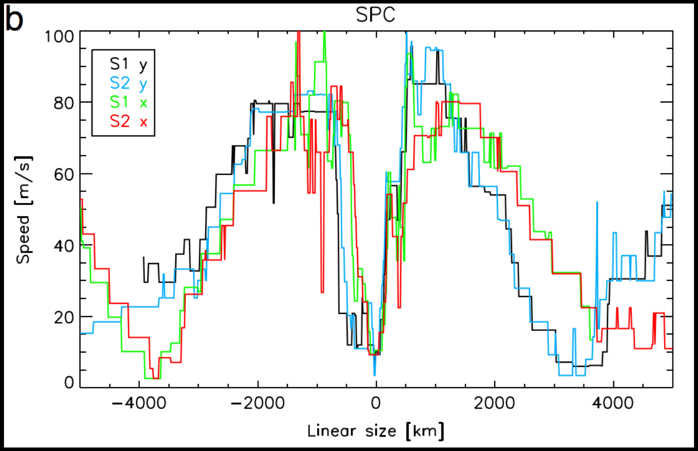


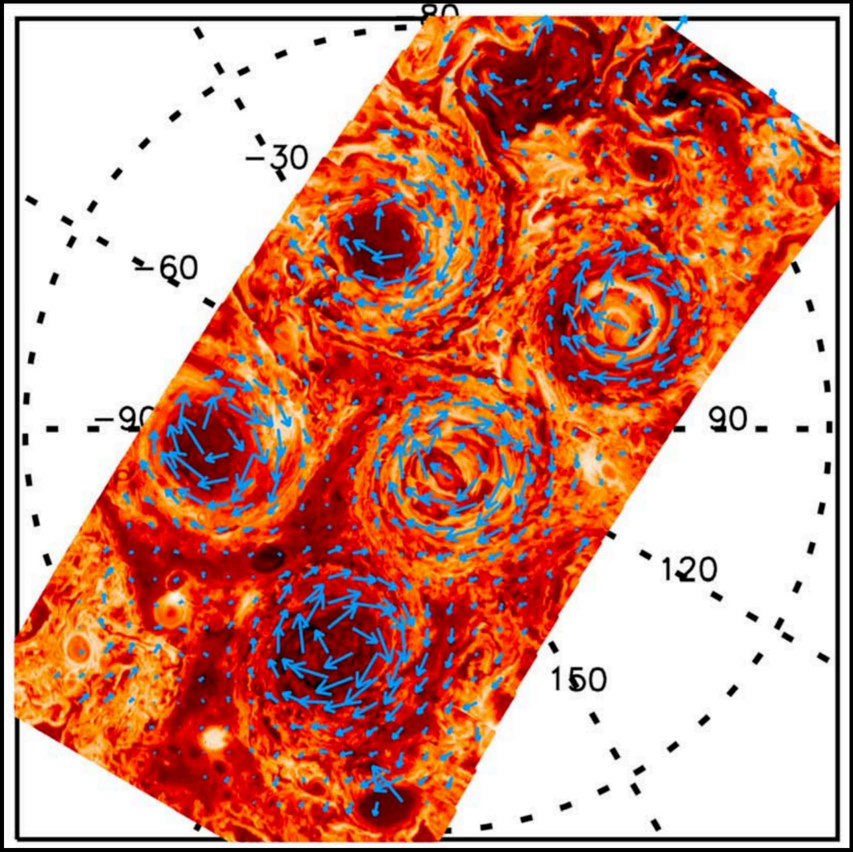
NASA / SwRI / MSSS / Gerald Eichstädt

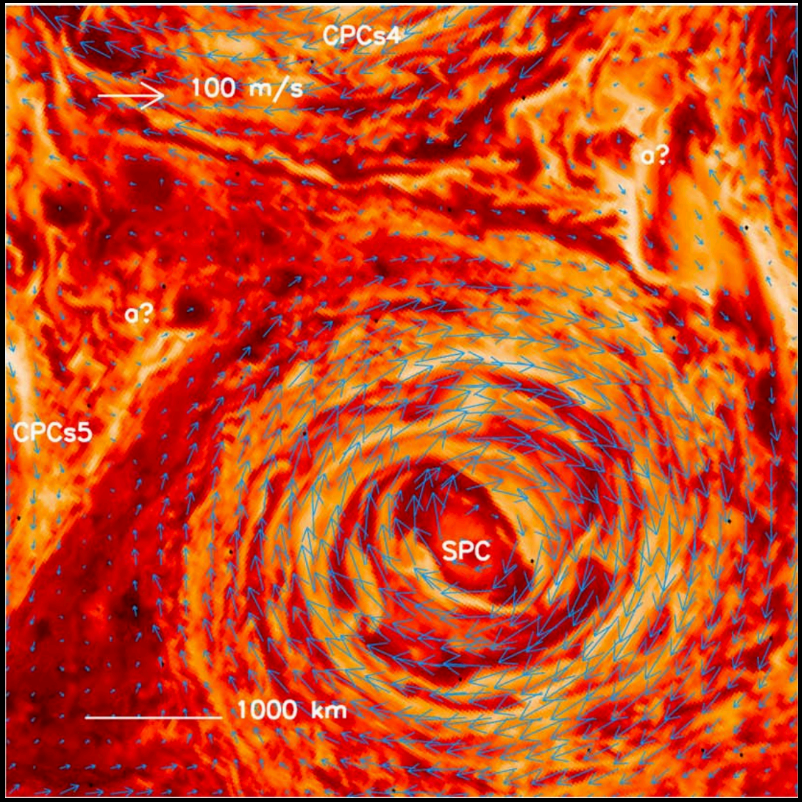
Polar Observations with Juno

Velocity tracking with JIRAM

(Jupiter Infrared Auroral Mapper)





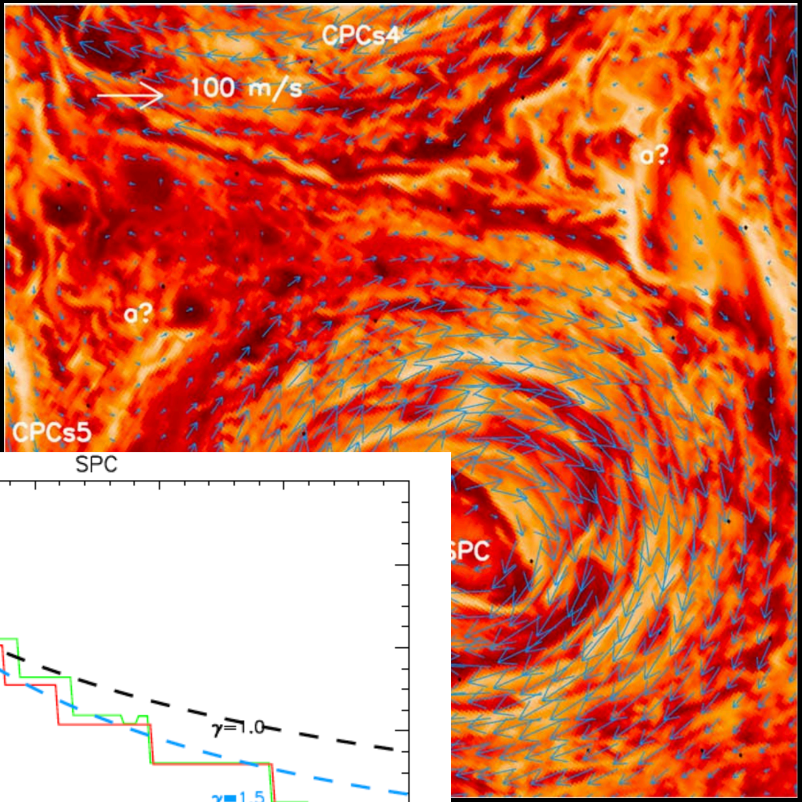


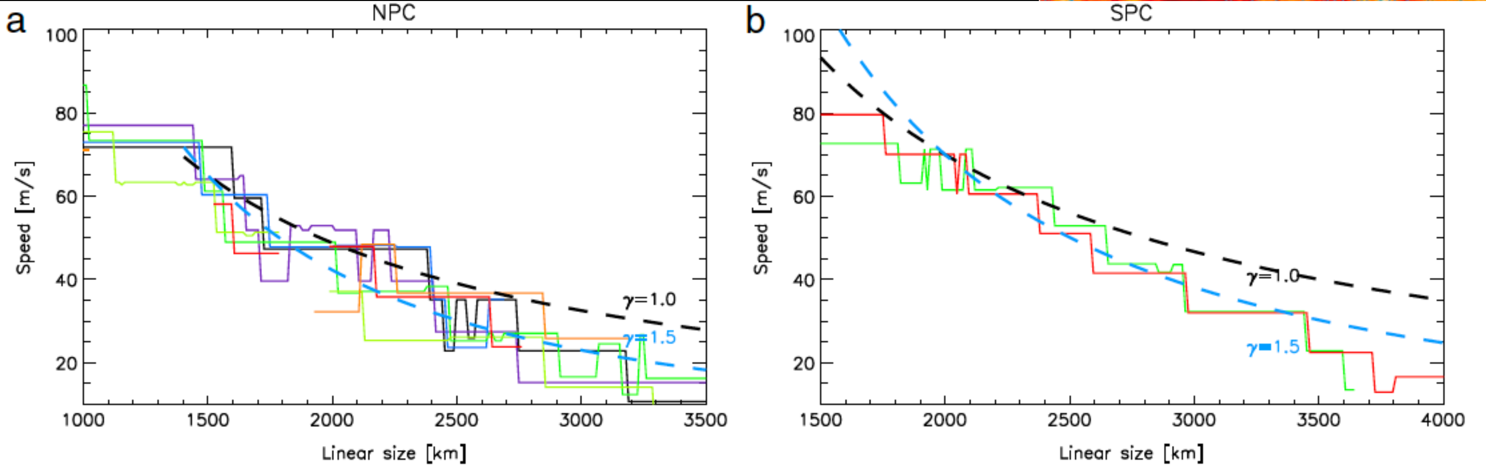
Grassi et al. 2018

Polar Observations with Juno

Velocity tracking with JIRAM

- Outer region of the central CPCs tangential velocity follows $v_t \sim r^{-\gamma}$ with γ between 1.0 and 1.5.
- Indicative of 2-dim. Shielded vortices, i.e. inverted vorticity at the border

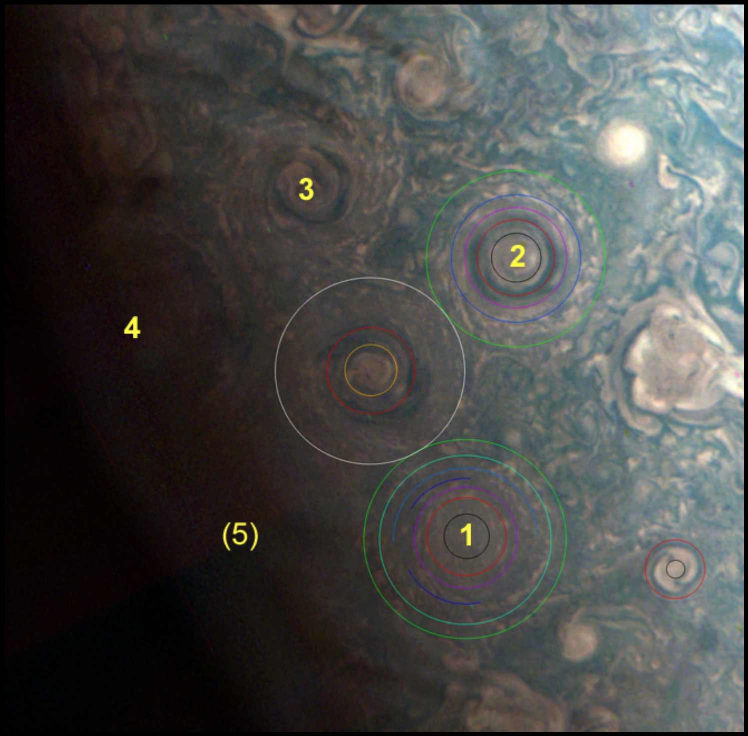


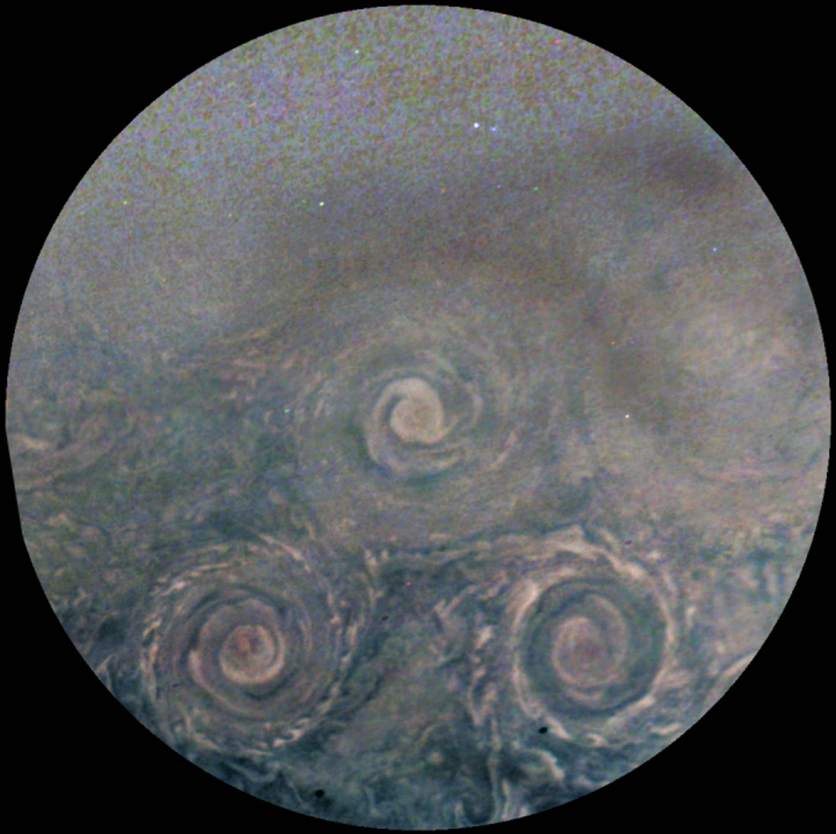


Grassi et al. 2018

Polar Observations with Juno

Velocity tracking with JunoCam

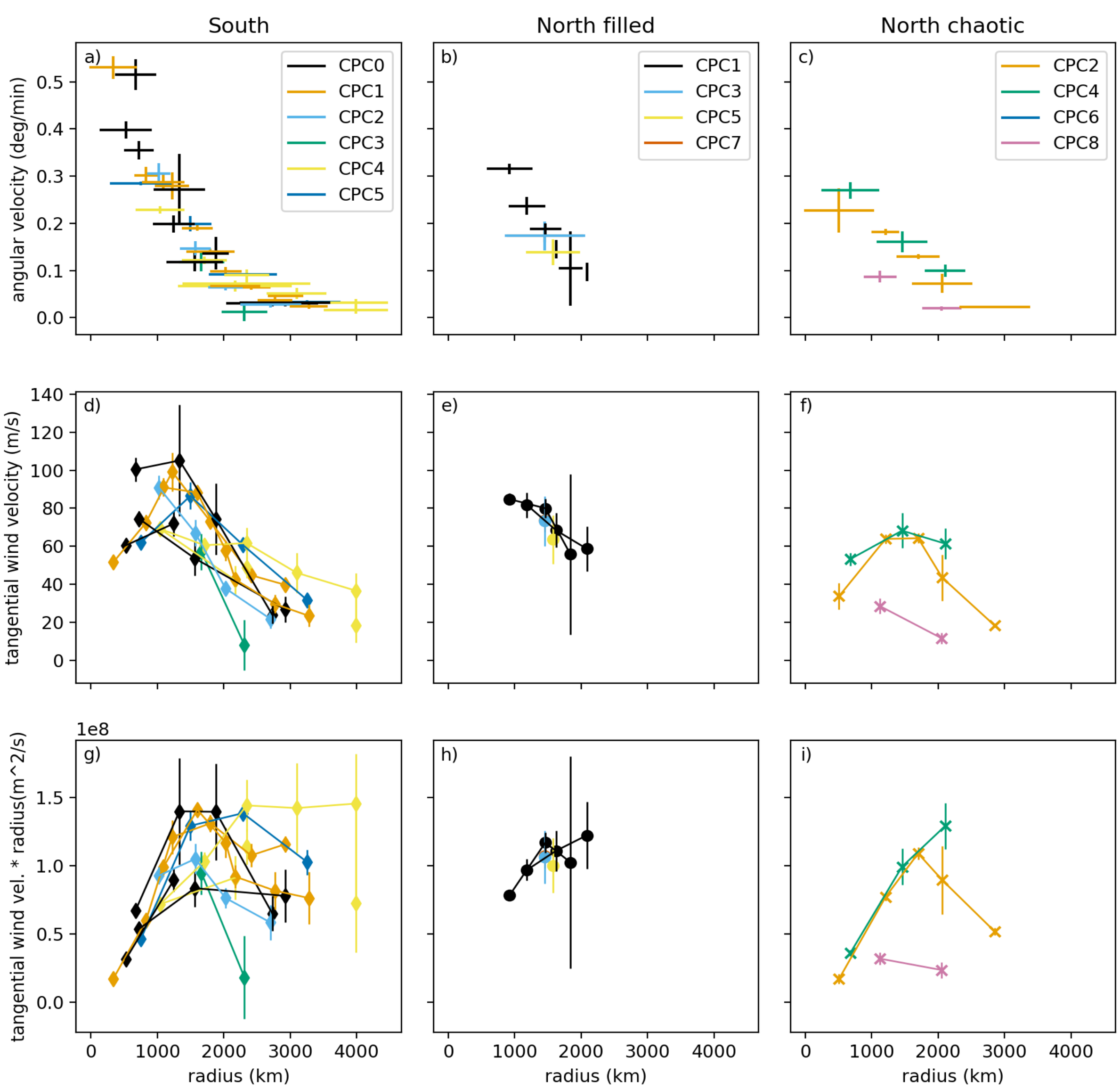


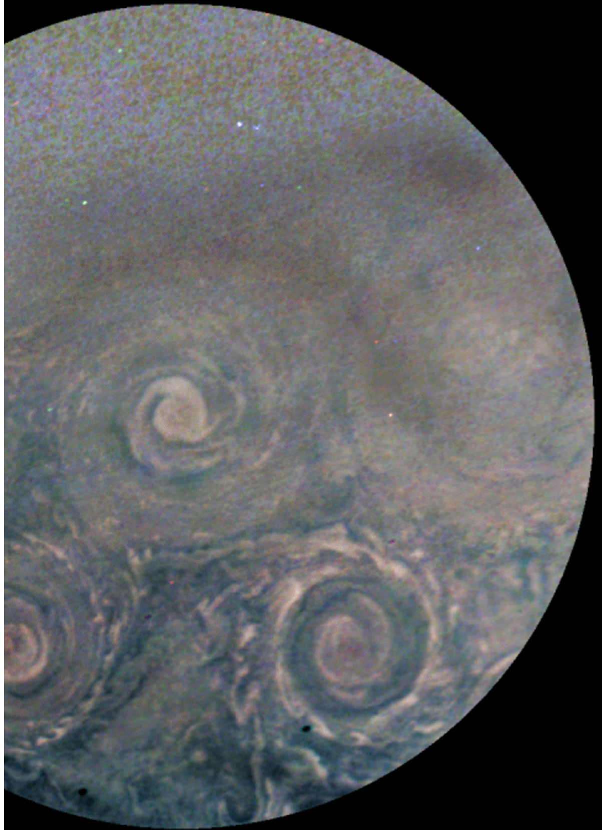


Tabataba-Vakili et al. in prep

Polar Observations with Juno

Velocity tracking with JunoCam

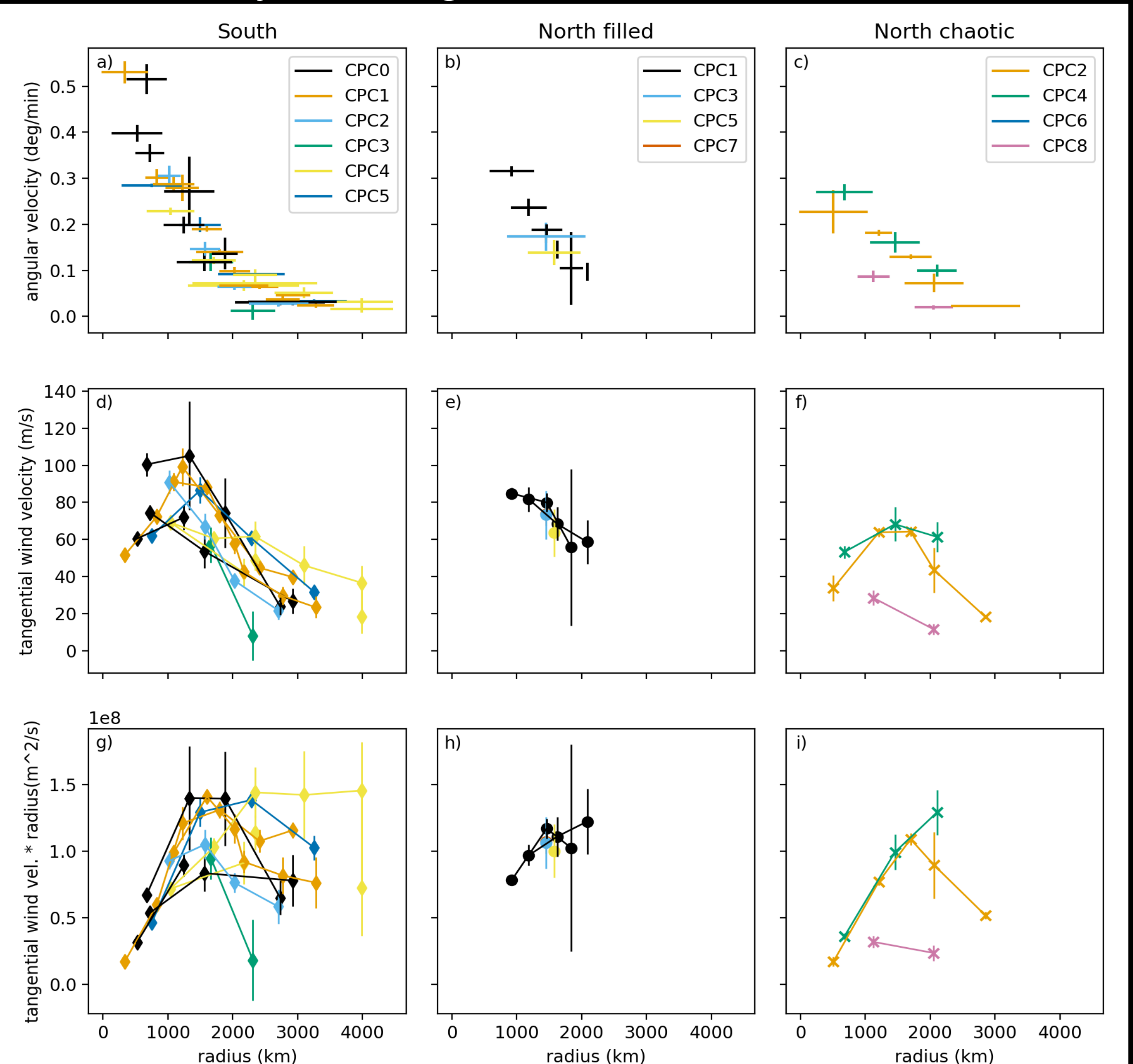




Tabataba-Vakili et al. in prep

Polar Observations with Juno

Velocity tracking with JunoCam



Angluar velocity omega

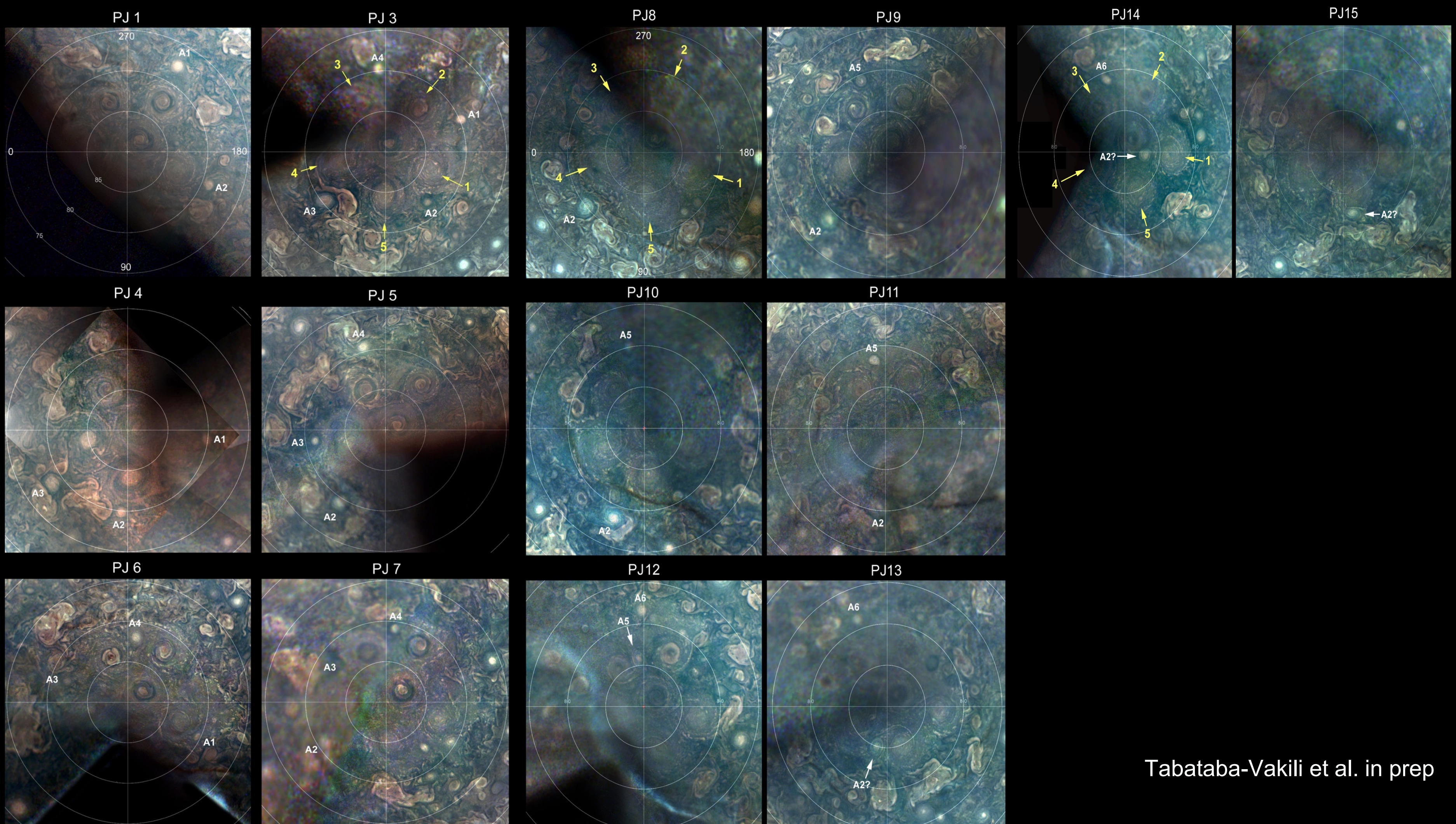
Tangential velocity vt=omega*r

Radius-corrected tan. velocity v_t*r to study v_t~r^-γ relationship. Straigt line = v_t~r^-1

Tabataba-Vakili et al. in prep

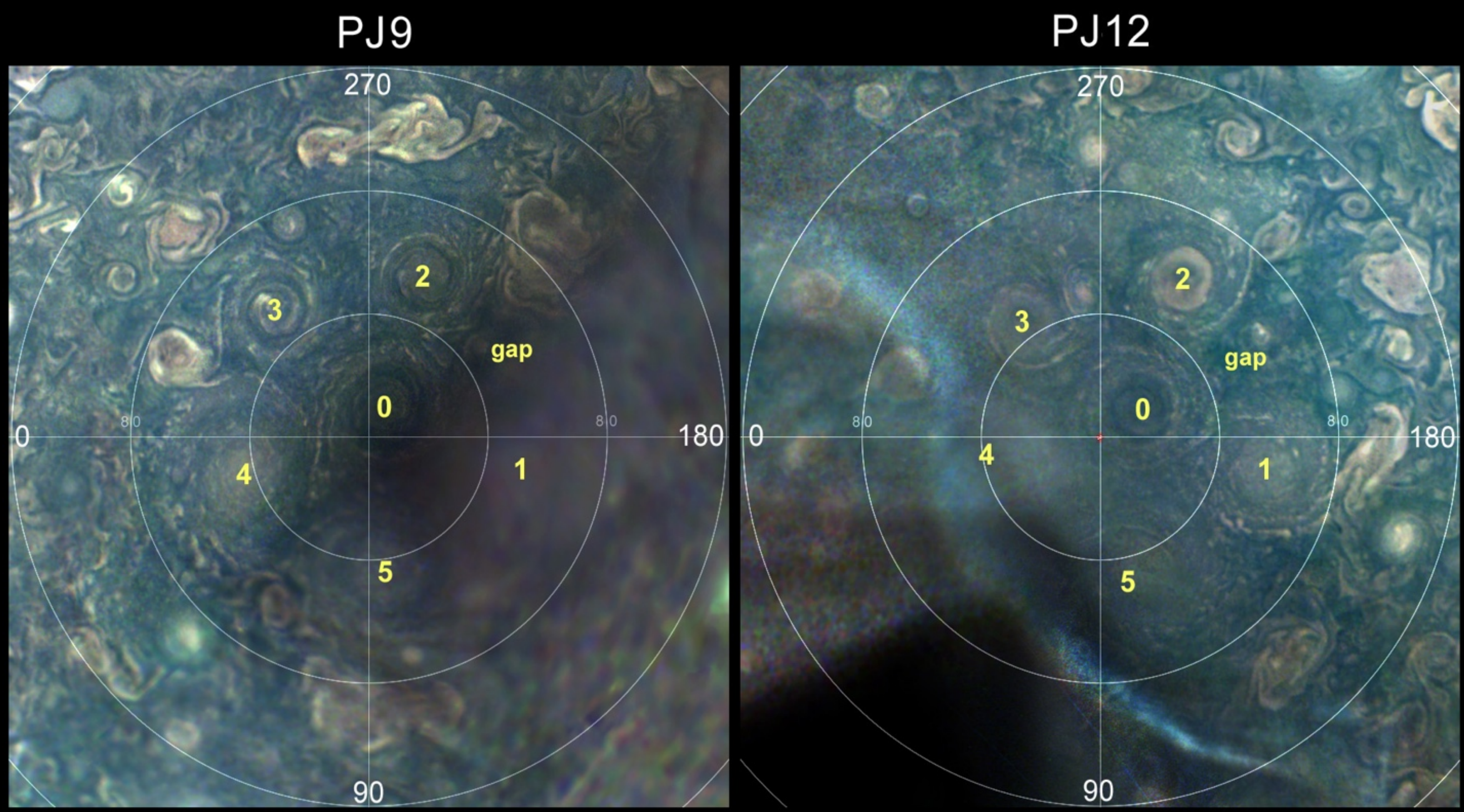
Polar Observations with Juno

South Pole: Long-term evolution



Tabataba-Vakili et al. in prep

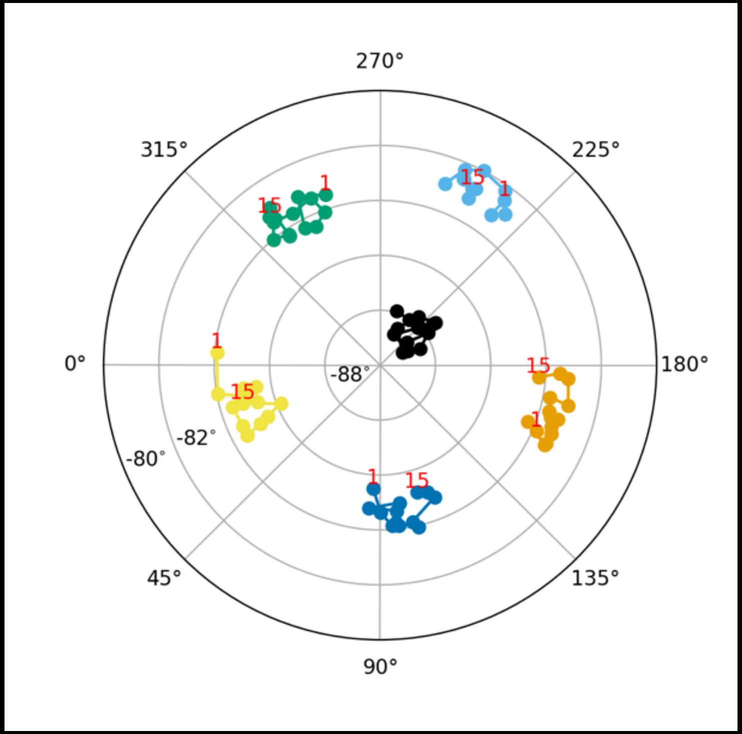
South Polar CPCs

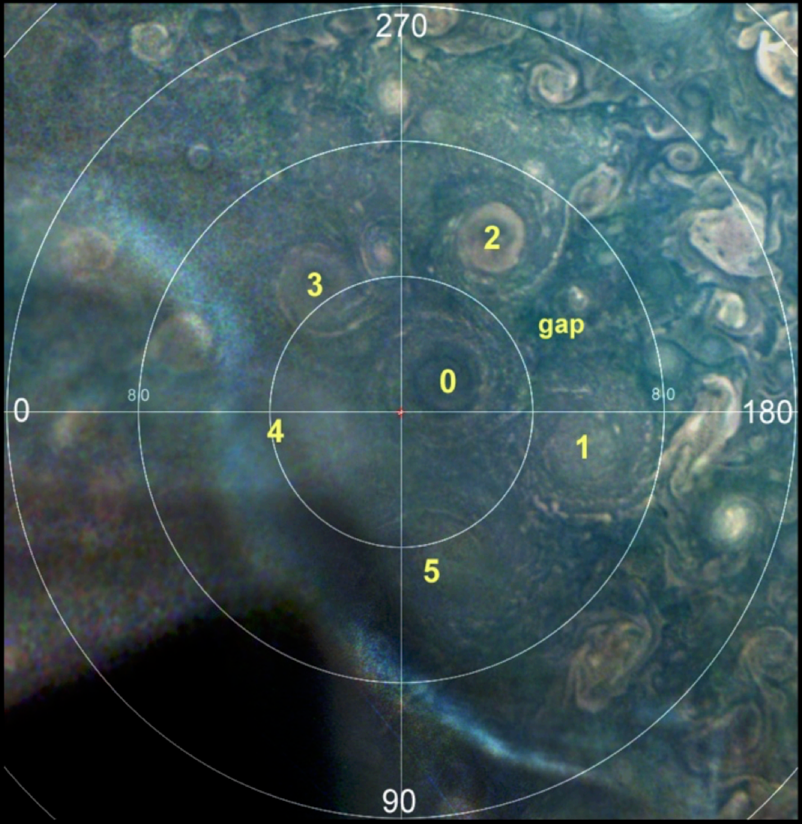


Tabataba-Vakili et al. in prep

Polar Observations with Juno

South Pole: Long-term evolution

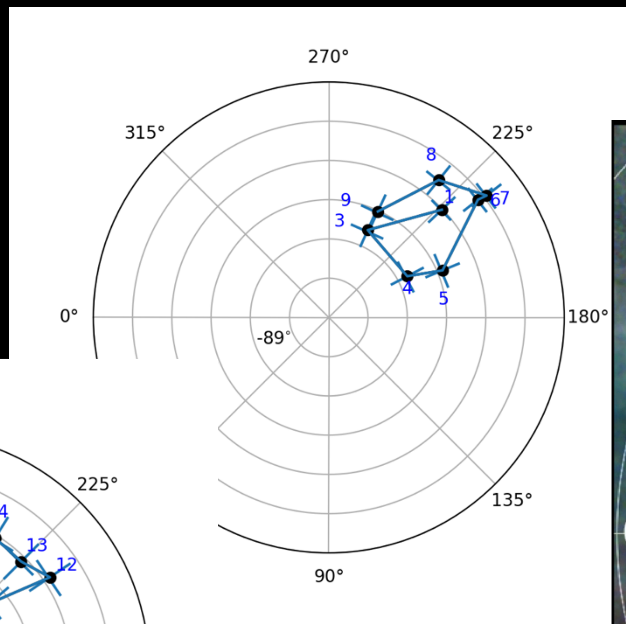


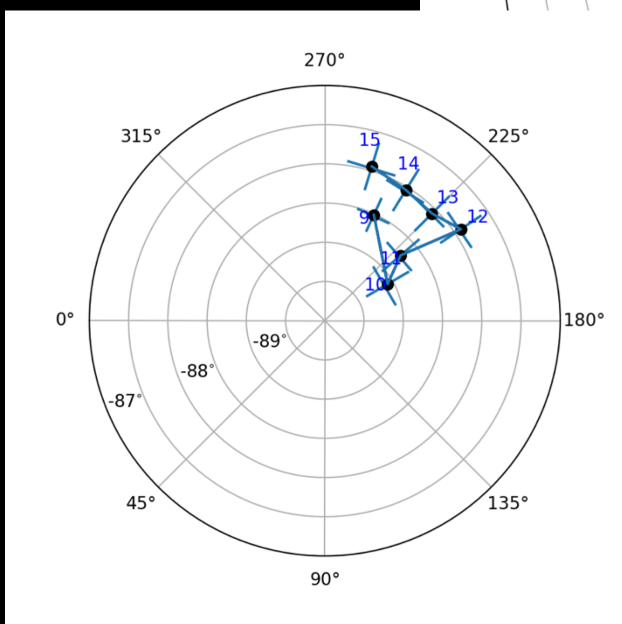


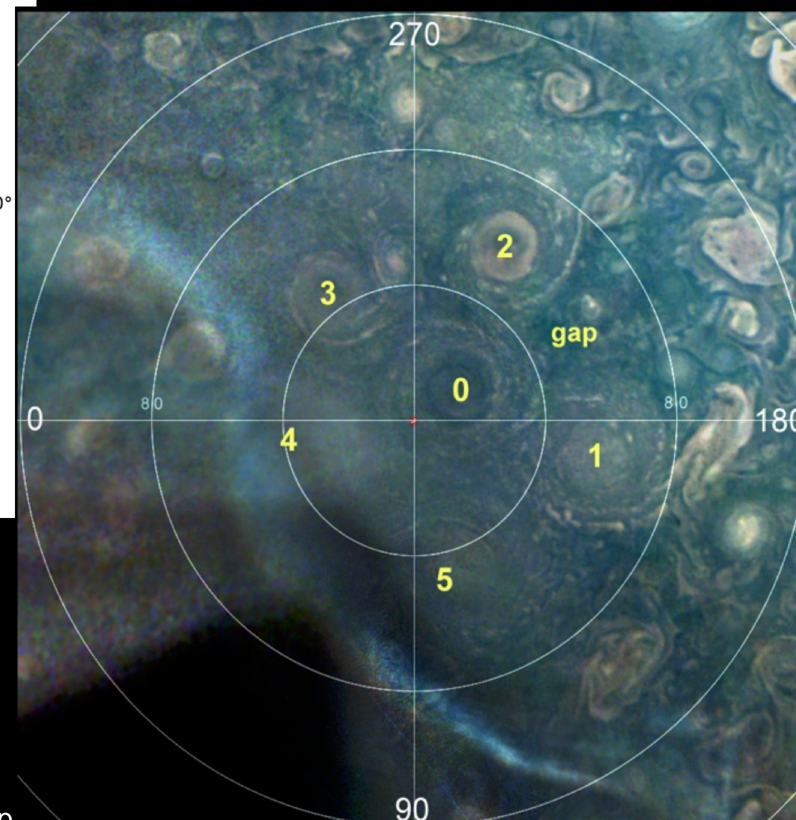
Tabataba-Vakili et al. in prep

Polar Observations with Juno

South Pole: Long-term evolution



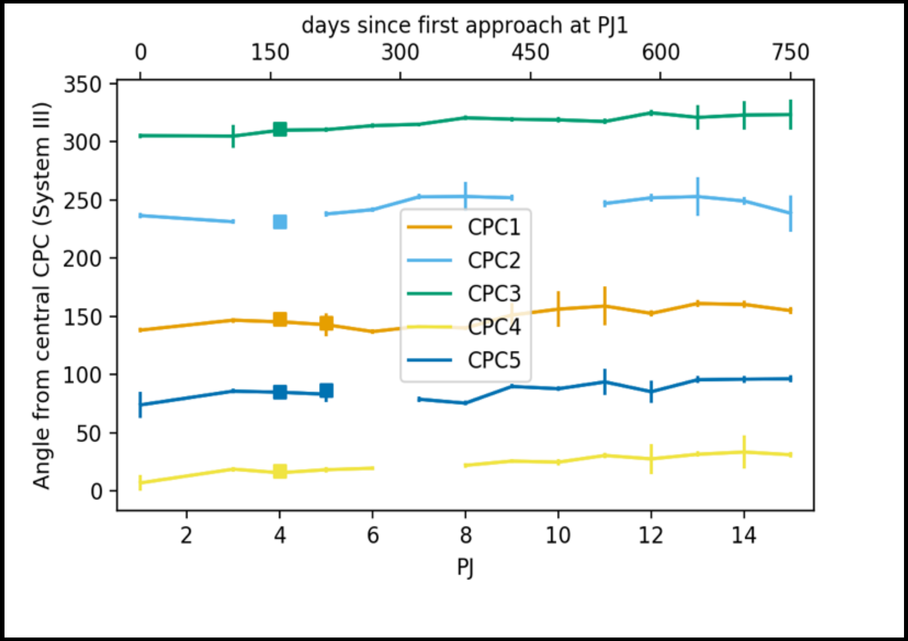


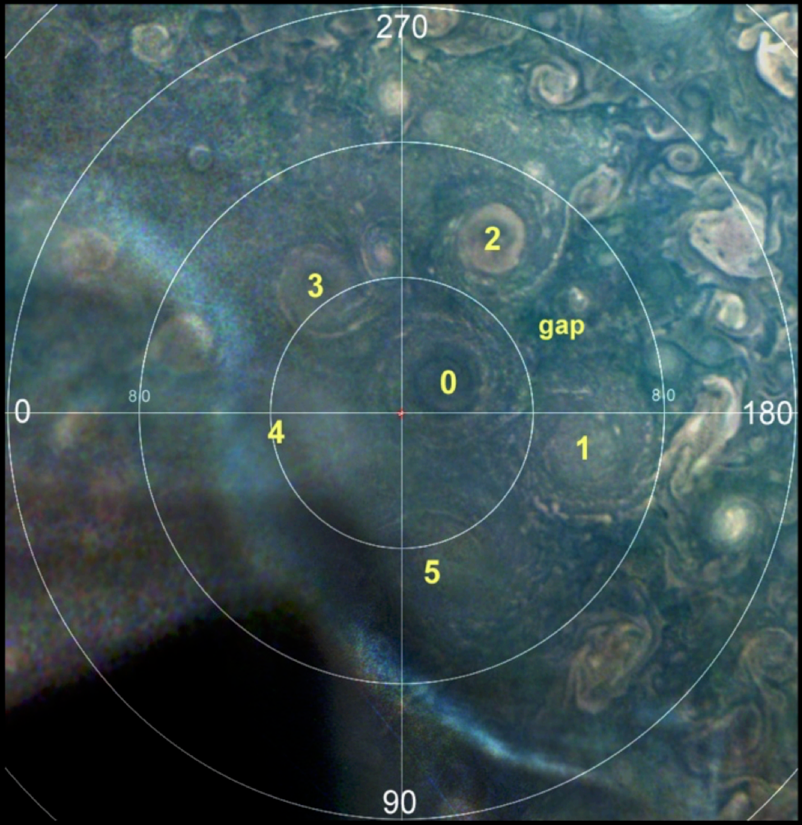


Tabataba-Vakili et al. in prep

Polar Observations with Juno

South Pole: Long-term evolution

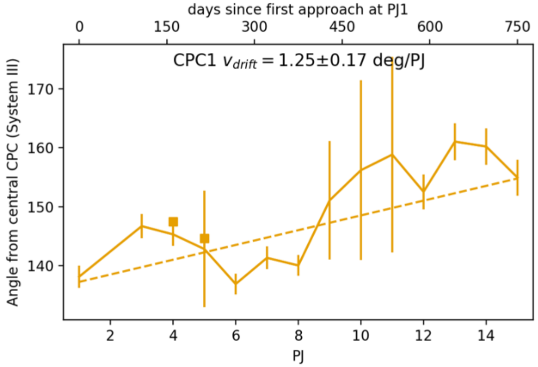


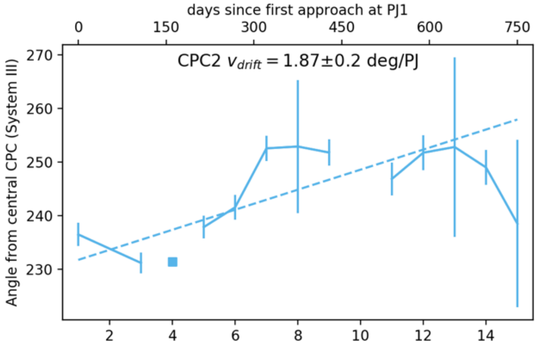


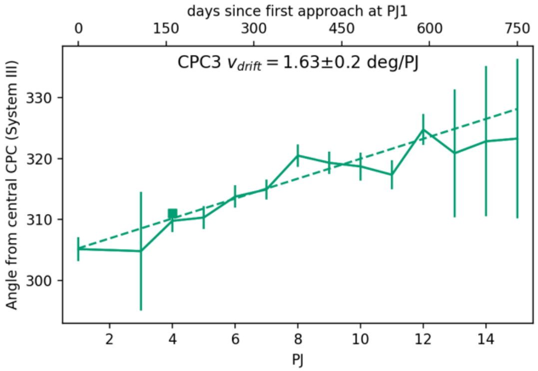
Tabataba-Vakili et al. in prep

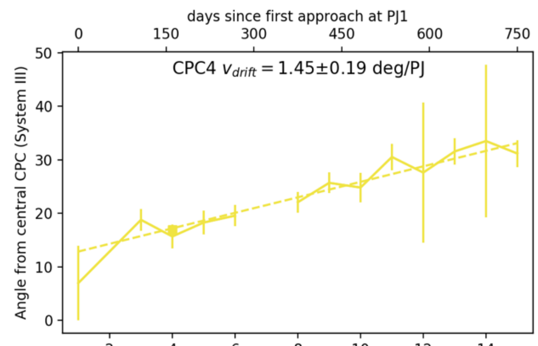
Polar Observations with Juno

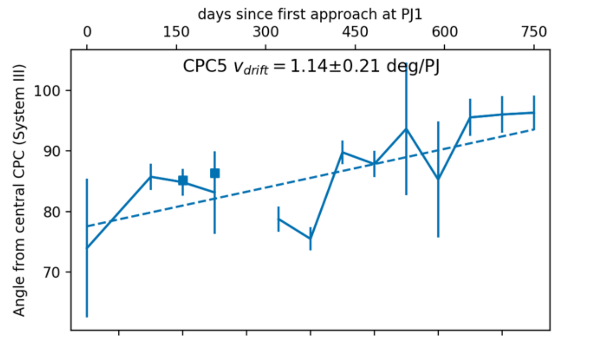
South Pole: Long-term evolution

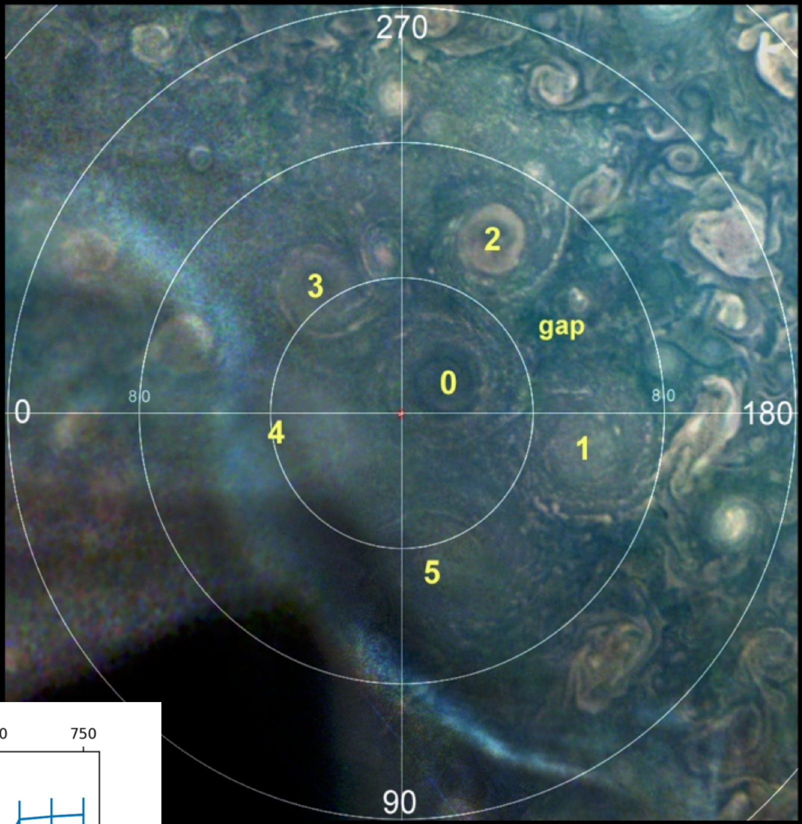






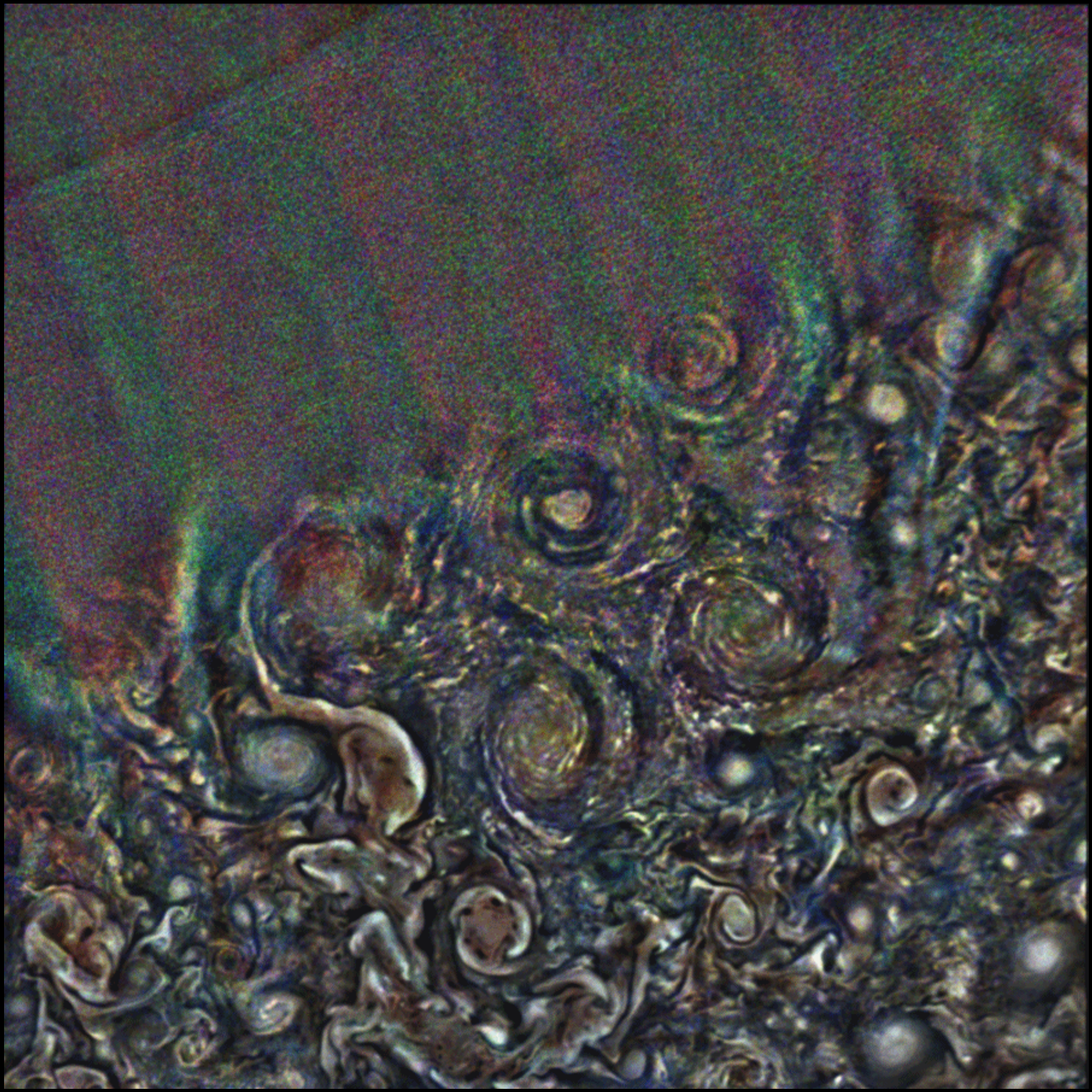






Tabataba-Vakili et al. in prep

South Polar CPCs

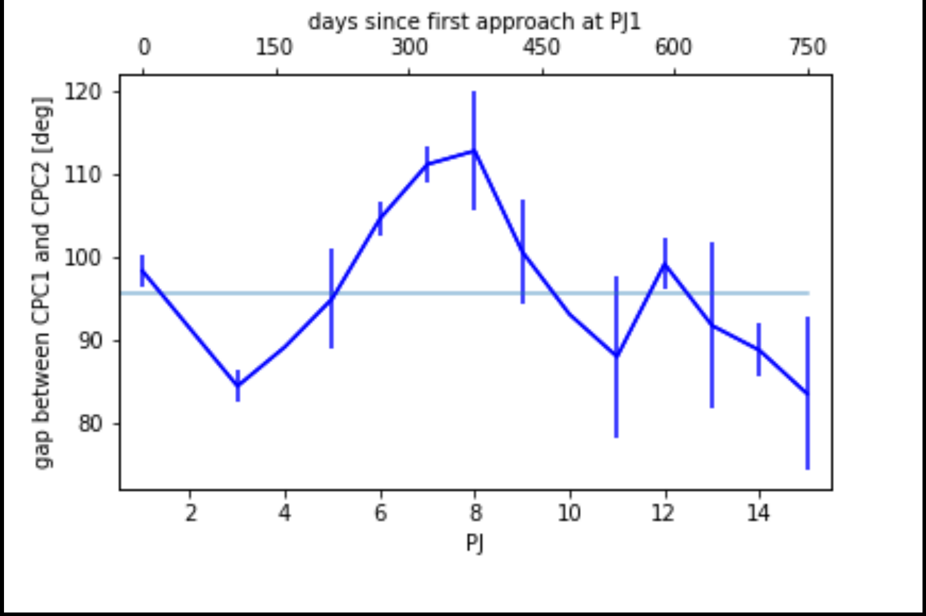


Tabataba-Vakili et al. in prep

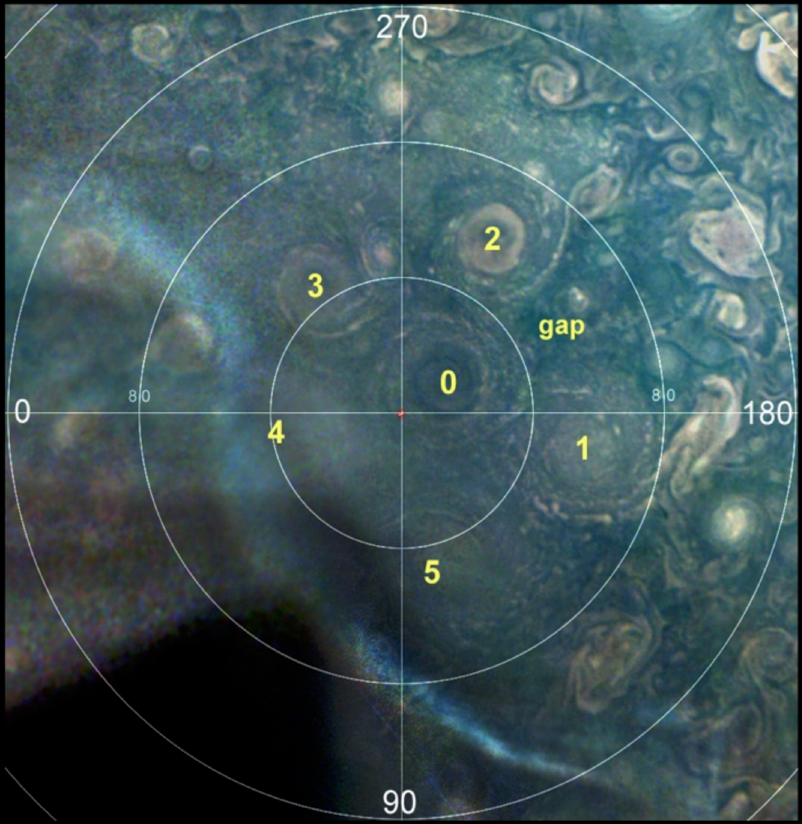
Polar Observations with Juno

South pole: Long-term evolution

Gap width



CPC (south pole)	1-2 (gap)	2-3	3-4	4-5	5-1
Mean gap width [deg]	97	71	67	63	63

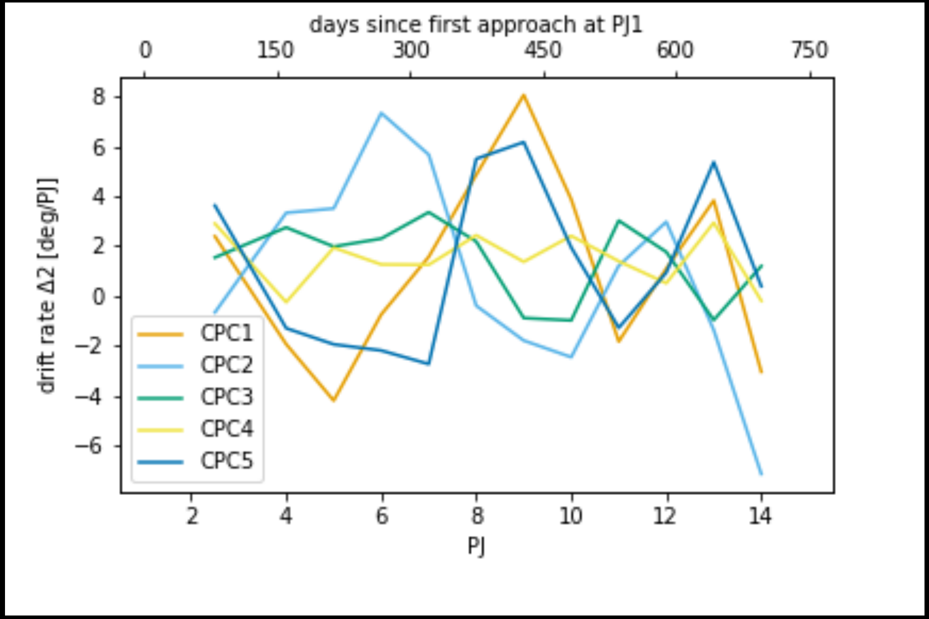


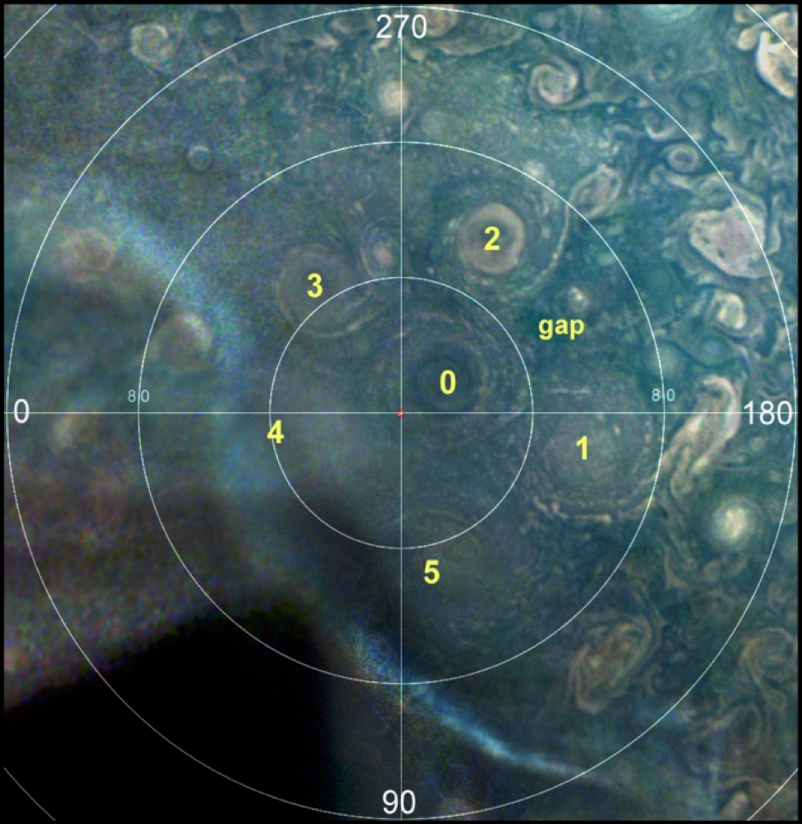
Tabataba-Vakili et al. in prep

Polar Observations with Juno

South pole: Long-term evolution

Instantaneous drift rate

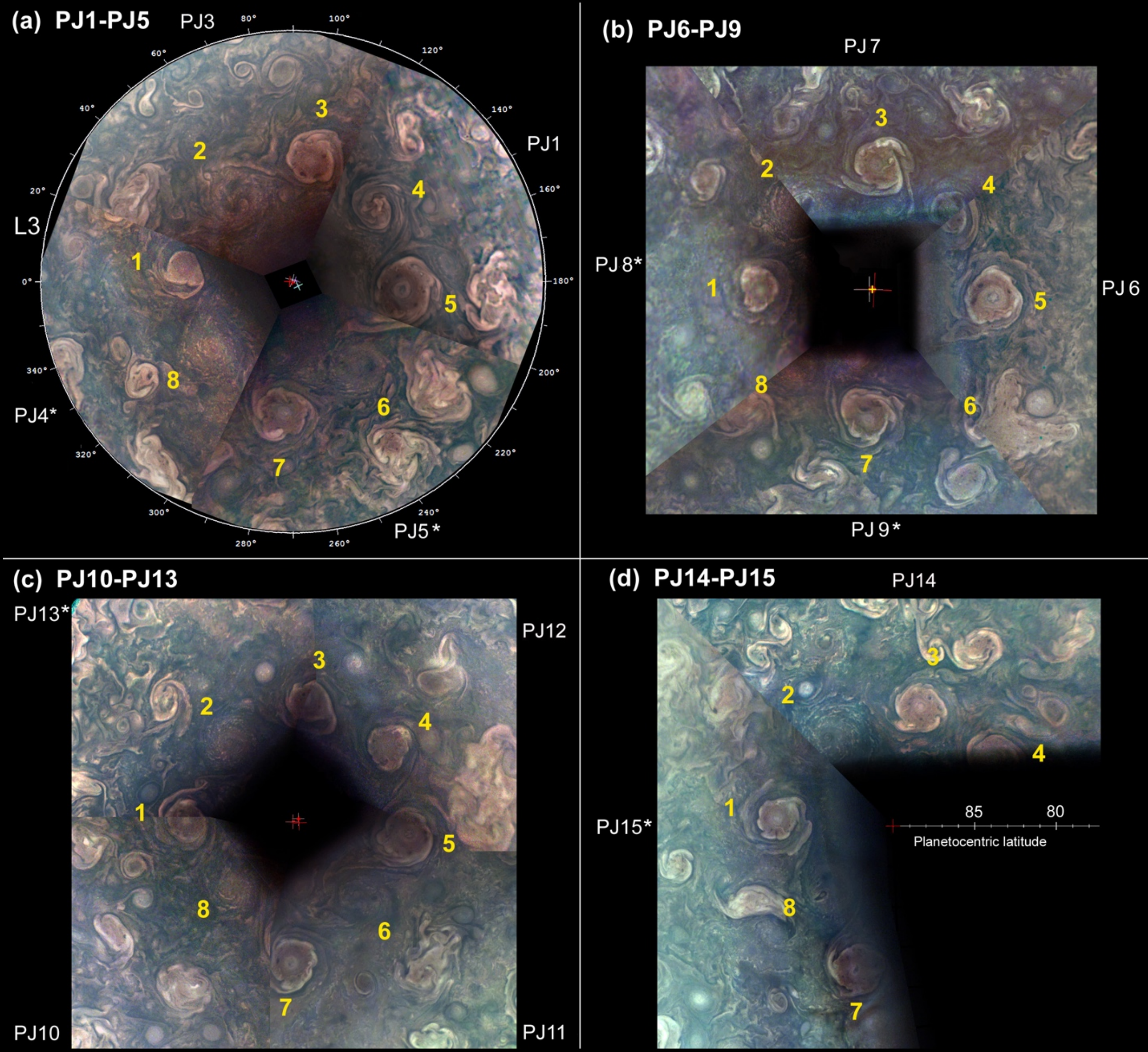




Tabataba-Vakili et al. in prep

Polar Observations with Juno

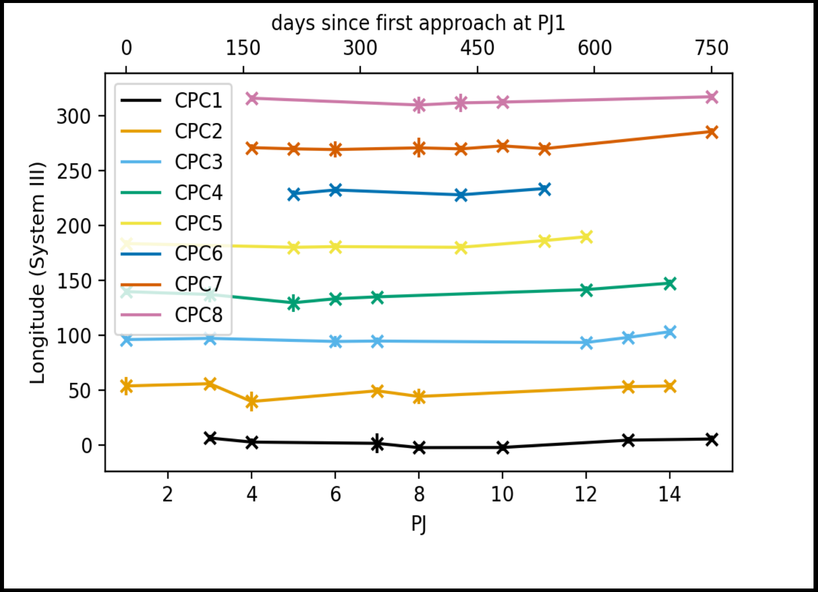
North pole: Long-term evolution

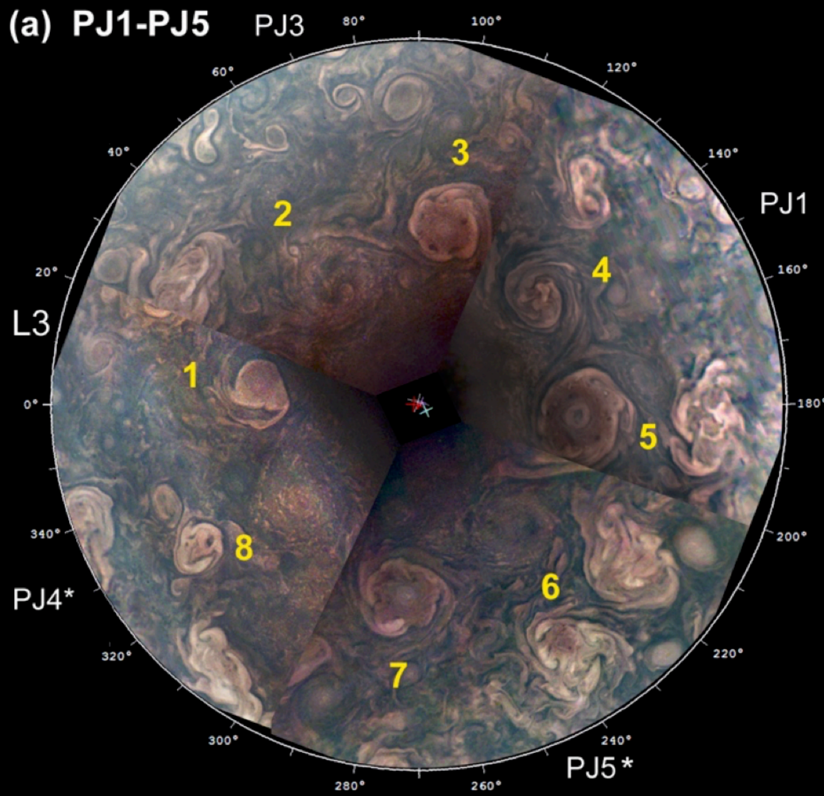


Tabataba-Vakili et al. in prep

Polar Observations with Juno

North pole: Long-term evolution

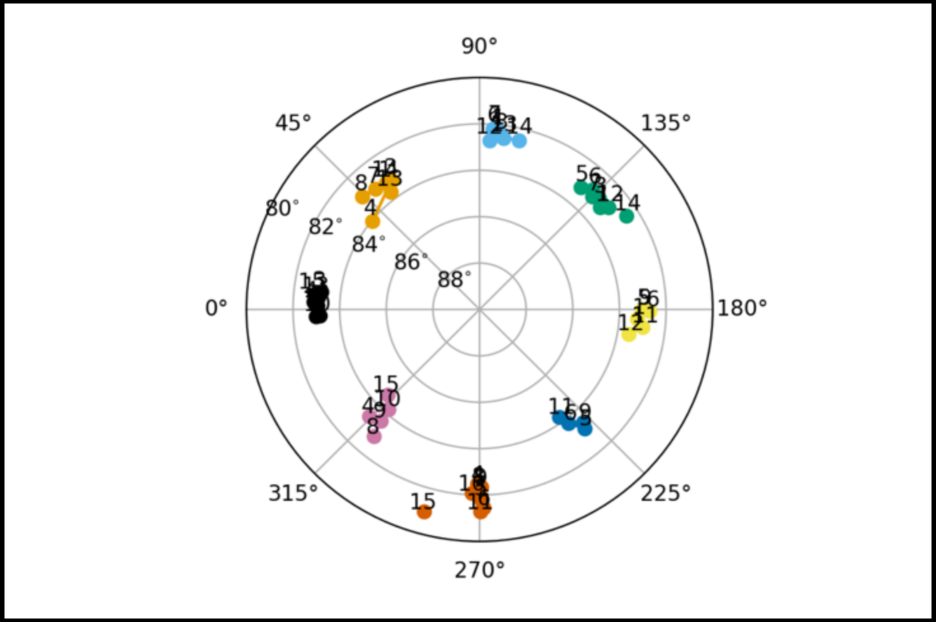


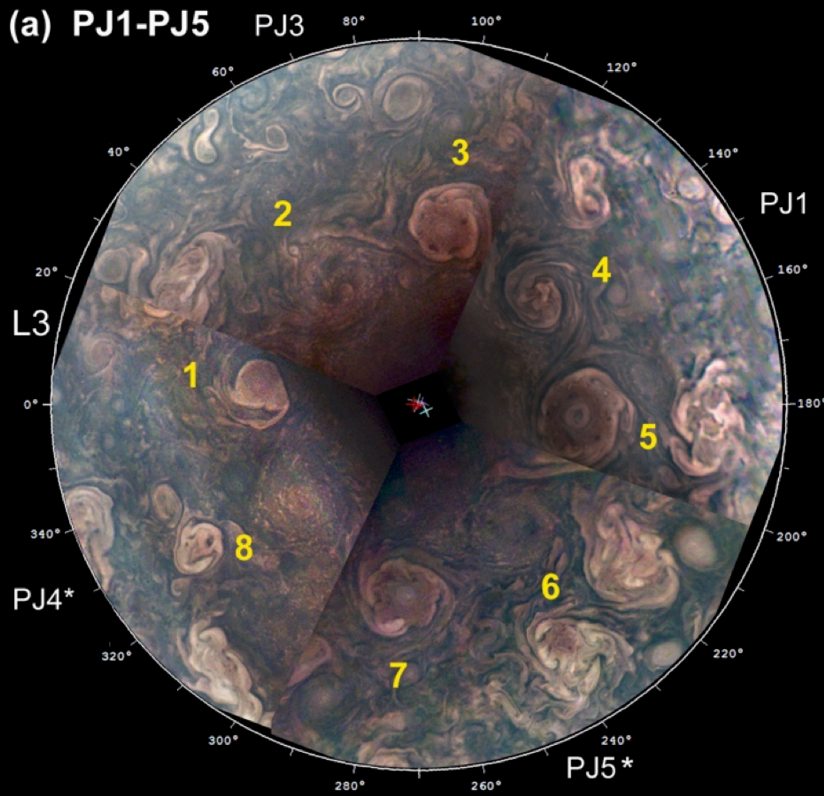


Tabataba-Vakili et al. in prep

Polar Observations with Juno

North pole: Long-term evolution

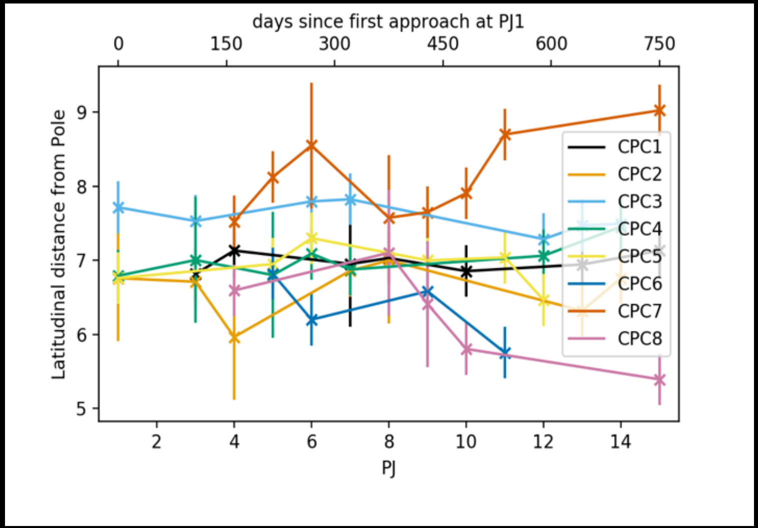


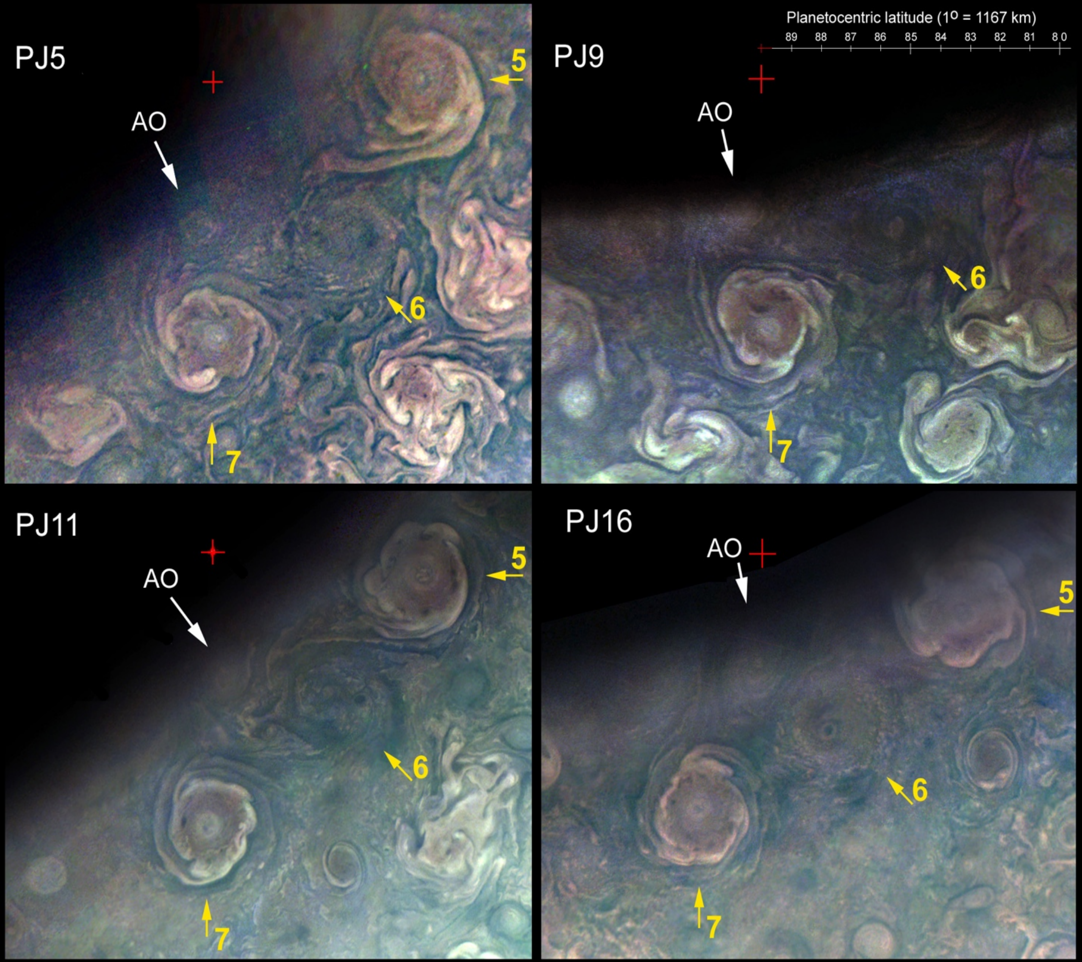


Tabataba-Vakili et al. in prep

Polar Observations with Juno

North pole: Long-term evolution

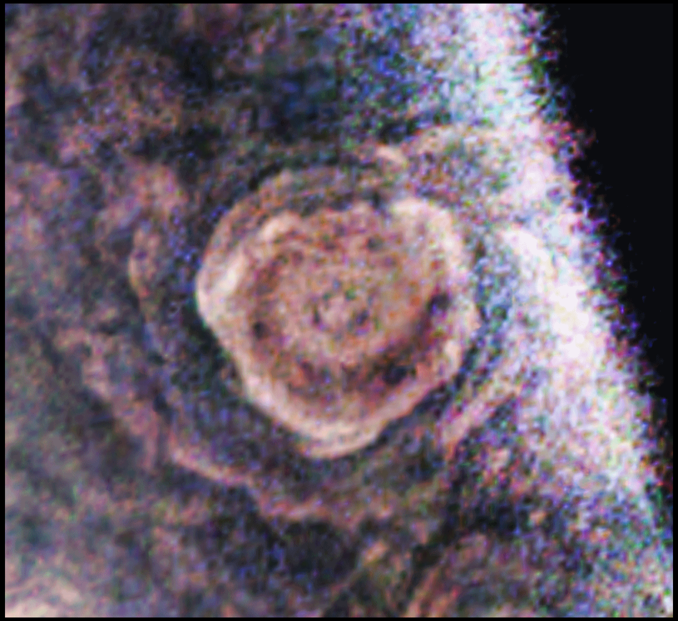


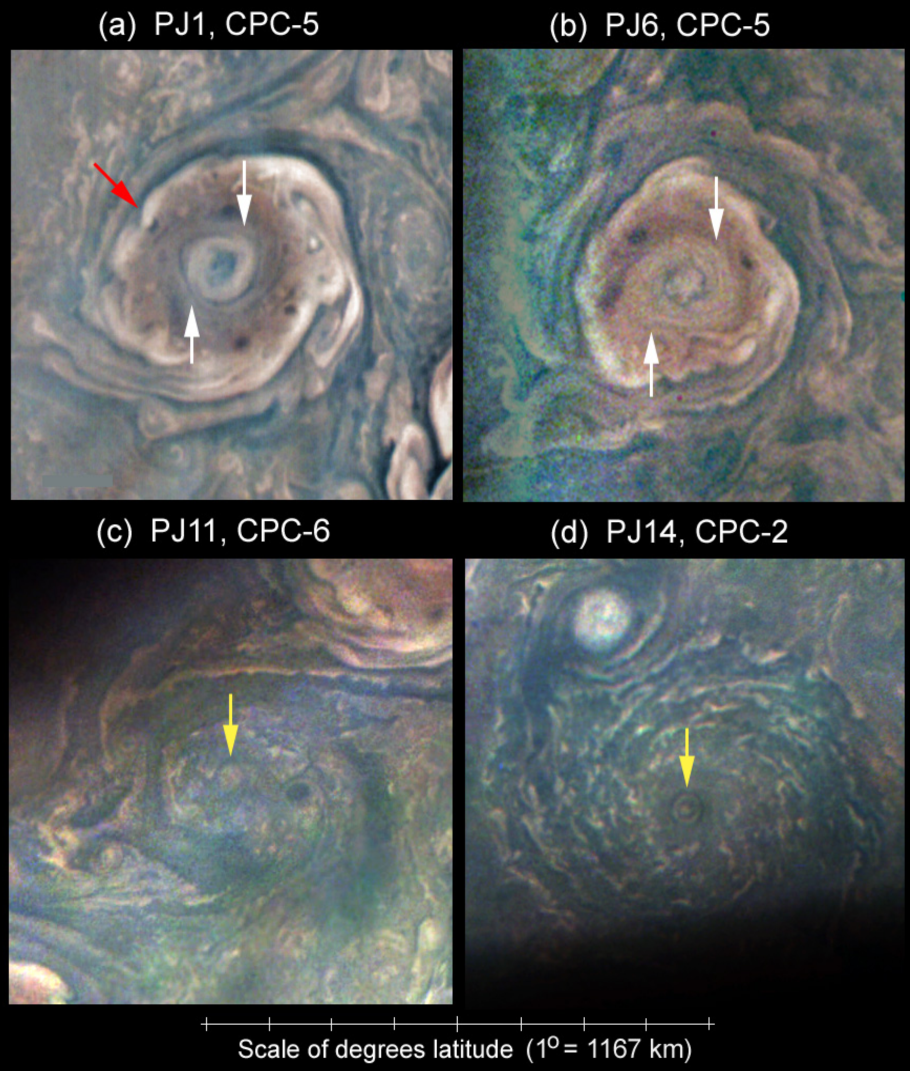


Tabataba-Vakili et al. in prep

Polar Observations with Juno

North pole: observations of internal counter-rotation



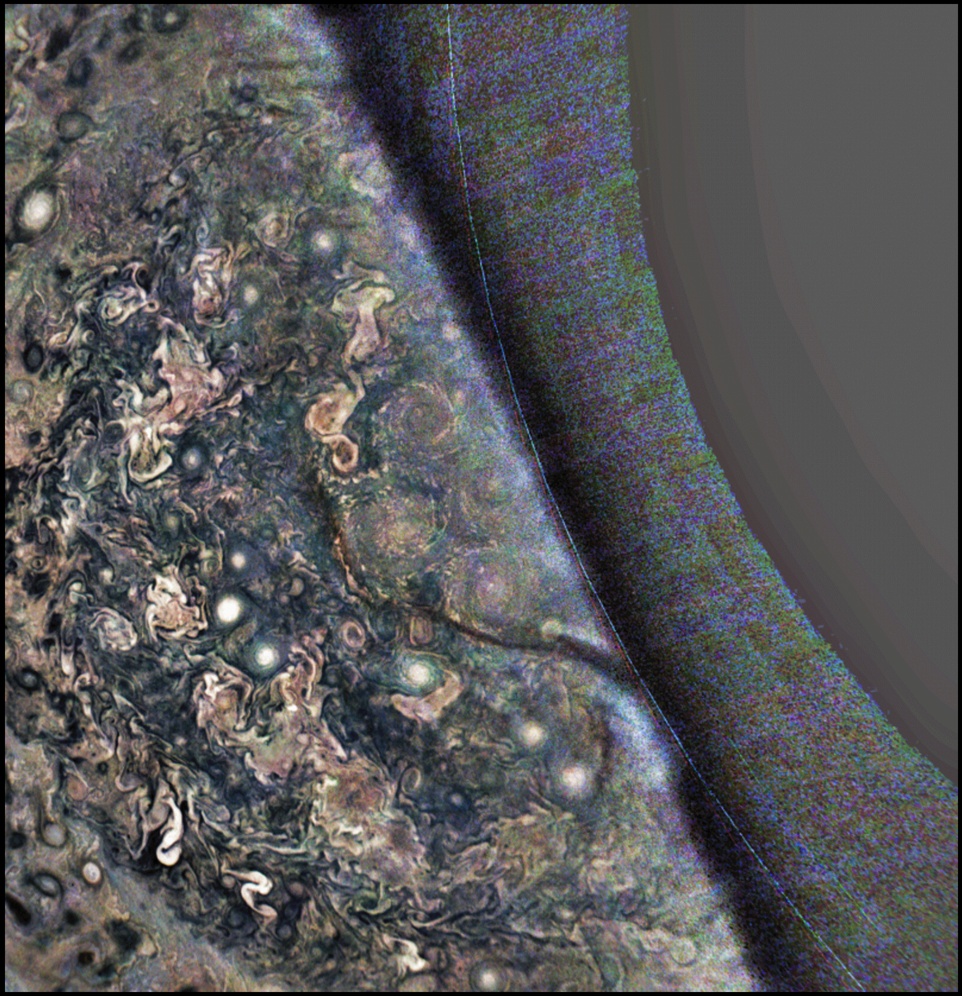


Tabataba-Vakili et al. in prep

Polar Observations with Juno

Region around the polar polygon.

- No apparent zonal jet visible from observations up to 2 hours

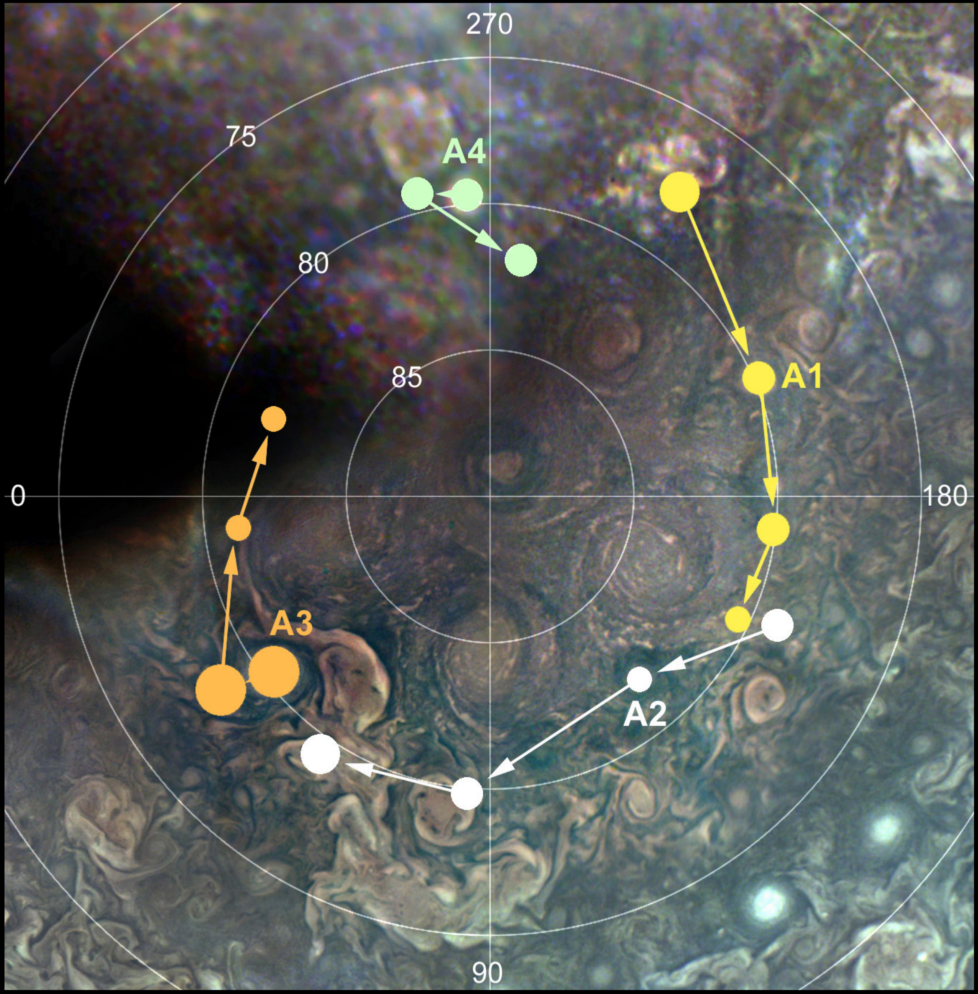


Tabataba-Vakili et al. in prep

Polar Observations with Juno

Region around the polar polygon.

- No apparent zonal jet visible from observations up to 2 hours
- Tracking of anticycloniic white ovals (AWOs) in the region
- Resulting zonal winds of…

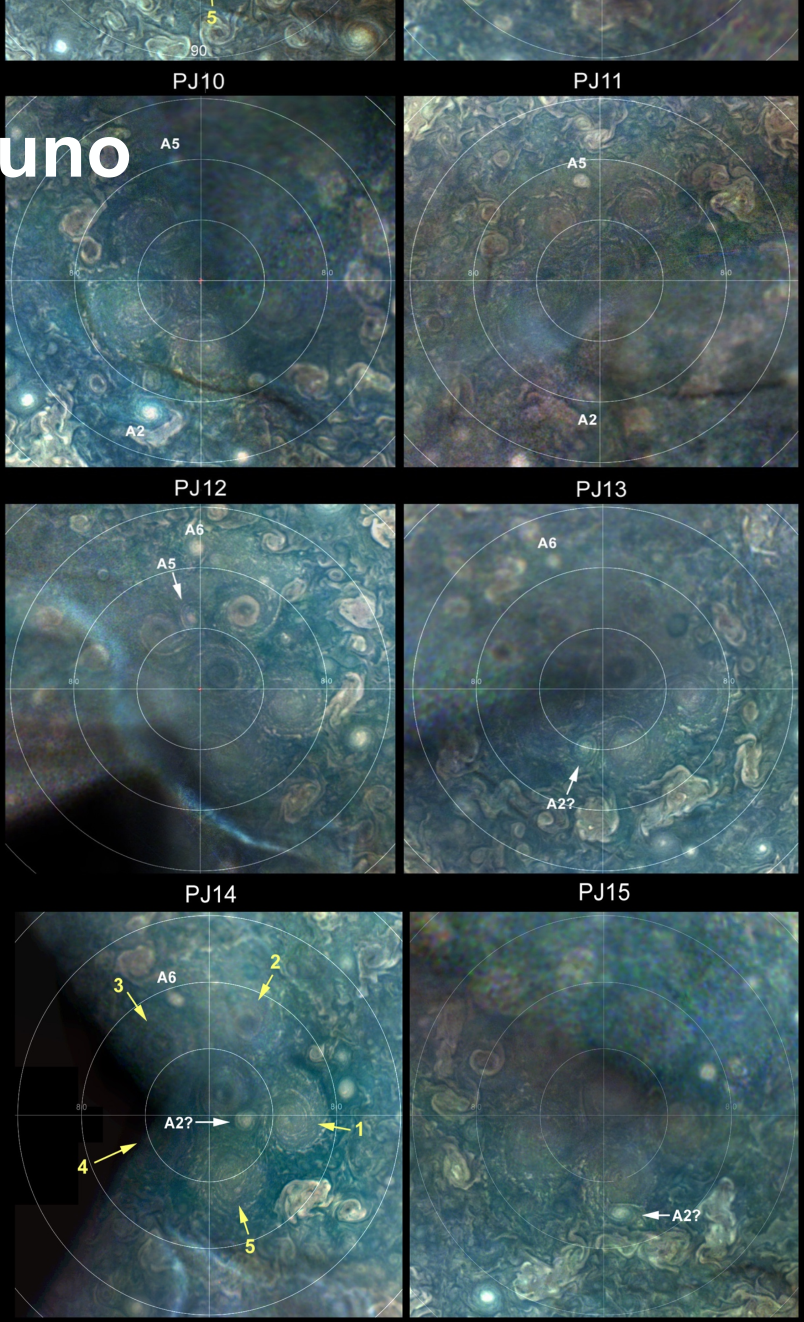


Tabataba-Vakili et al. in prep

Polar Observations with Juno

Region around the polar polygon.

- No apparent zonal jet visible from observations up to 2 hours
- Tracking of anticycloniic white ovals (AWOs) in the region
- Resulting zonal winds of…
- AWOs likely move around the CPCs as well (PJ 10-15)

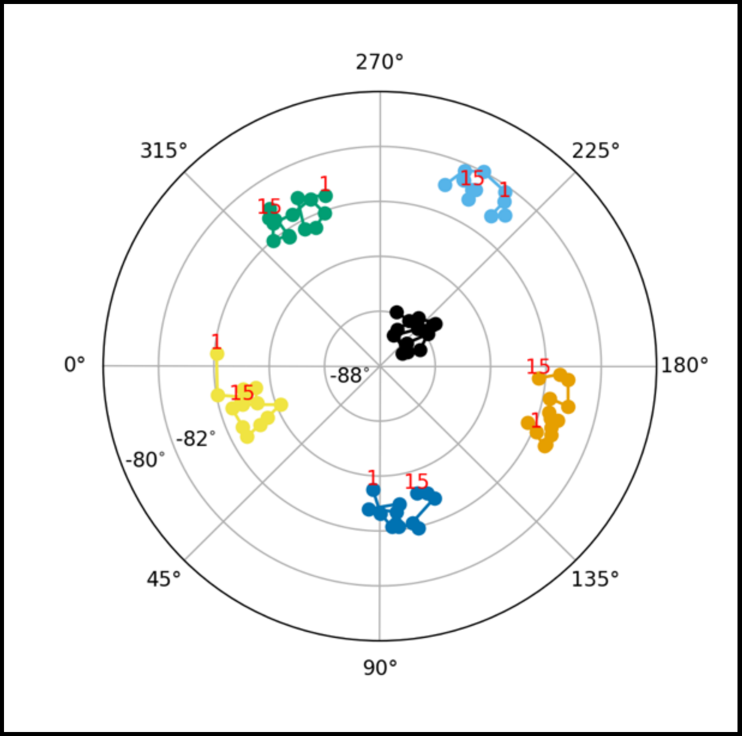


Tabataba-Vakili et al. in prep

Polar Observations with Juno

South Pole: Cyclone Structure

- 5-point outer structure appear to be centered about the central cyclone rather than the rotational pole
- Rotation rate of the pentagon is 1.5+/-0.2 degrees per perijove.
- Outer cyclones do not revolve around the pole uniformly, instead they “wobble” back and forth in longitude
- Central cyclone has a circular motion with a period of 8 PJs

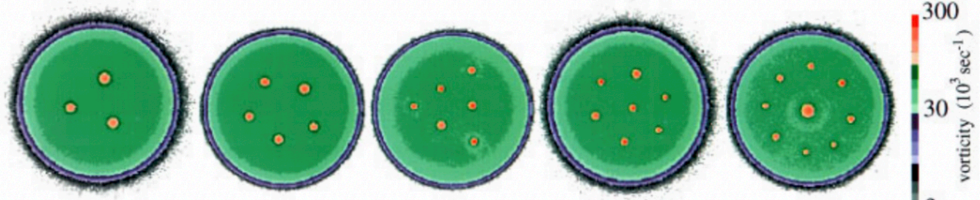


Tabataba-Vakili et al. in prep

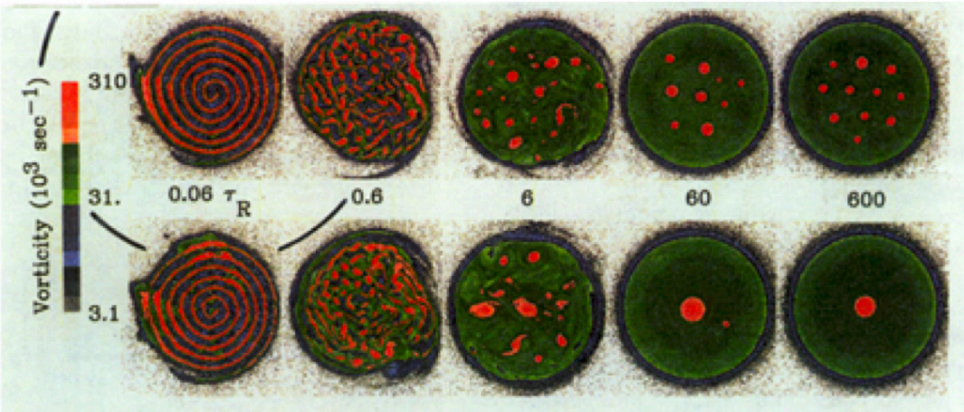
Comparison with Theory

Vortex Crystals

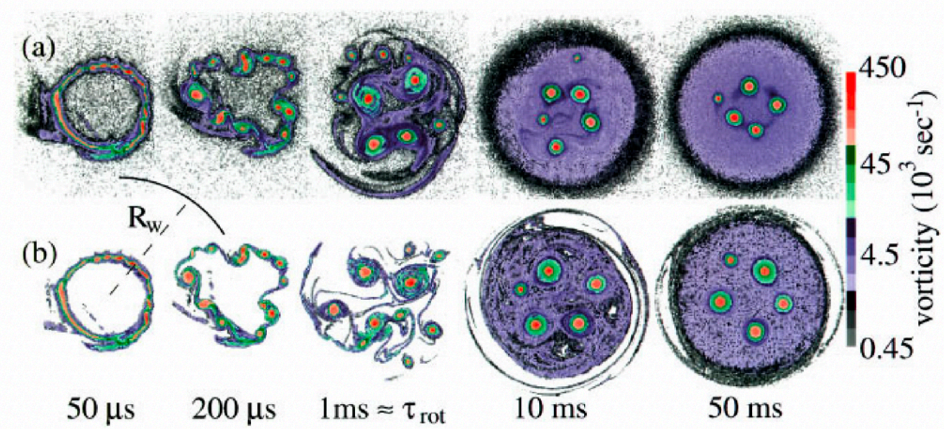
- Constellations of vortices as rare stable solution for initial turbulence.
- Observed in magnetized plasma columns and rotating superfluids to represent 2d turbulence.
- Effect is described by 2d Euler equations.
  - No friction
  - Only positive vorticity
- Formation to achieve maximum entropy.
- In lab and models: stable for around 400 rotations, after which minute frictional effects cause dissipation.



Several stable configurations of vortex crystals. (Fine et al. 2005)



The evolution of two vortex experiments with slightly different viscosities. (Fine et al. 2005)

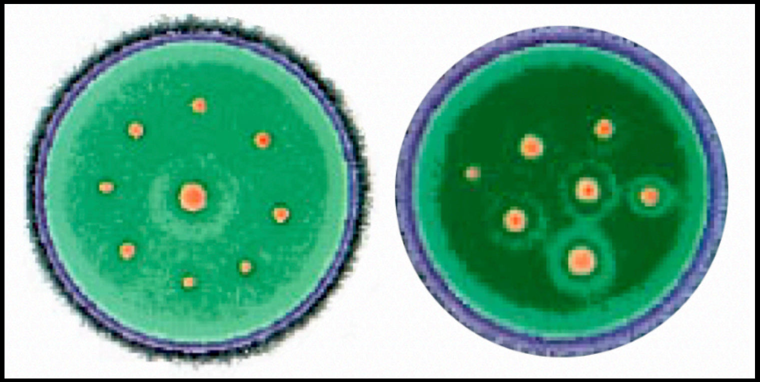


Experiment (a) and simulation (b) of vortex crystal evolution with the same initial conditions. (Schecter et al. 1999)

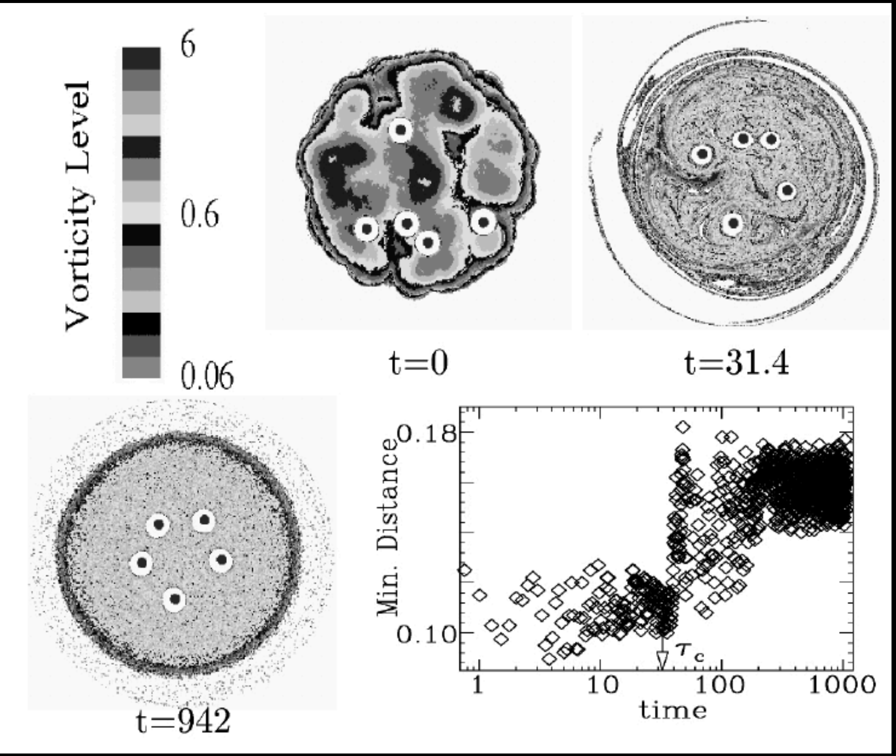
Comparison with Theory

Vortex Crystals

- Examples of
  - Shape
  - Time evolution



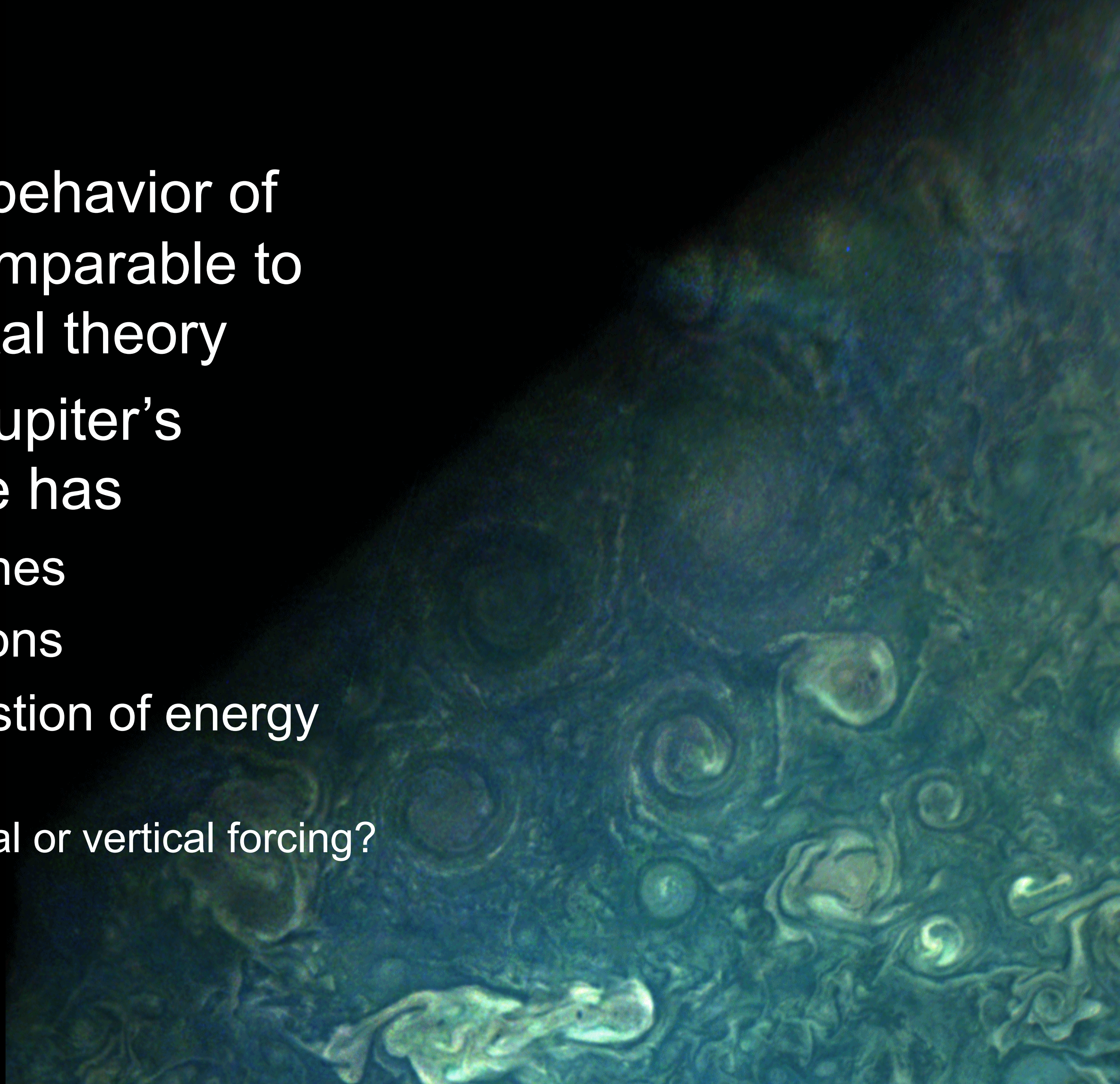
Fine et al. (1995)



Jin and Dubin (2000)

Summary

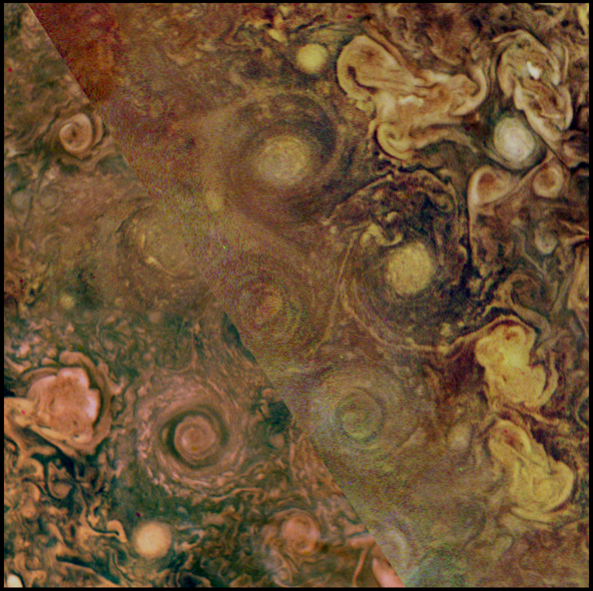
- Long-term behavior of CPCs is comparable to vortex crystal theory
- However, Jupiter’s atmosphere has
  - Anti-cyclones
  - 3 dimensions
  - Open question of energy source
    - Horizontal or vertical forcing?



Open Questions

- How are vortex crystrals in atmospheres possible?
- What is the difference between polar cyclones on Saturn vs Jupiter?
- What processes hinder mergers of cyclones?

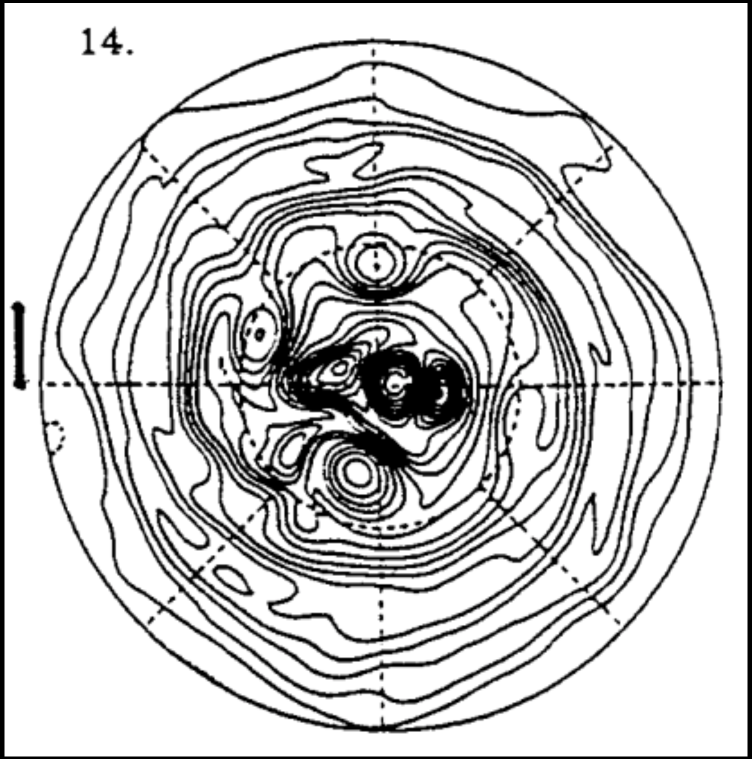
Jupiter



Open Questions

Polar cyclones on giant planets

- Shallow-water models of giant planets have circumpolar cyclones (e.g. Cho and Polvani, 1996), but so far none have resulted in vortex-crystal-like constellations

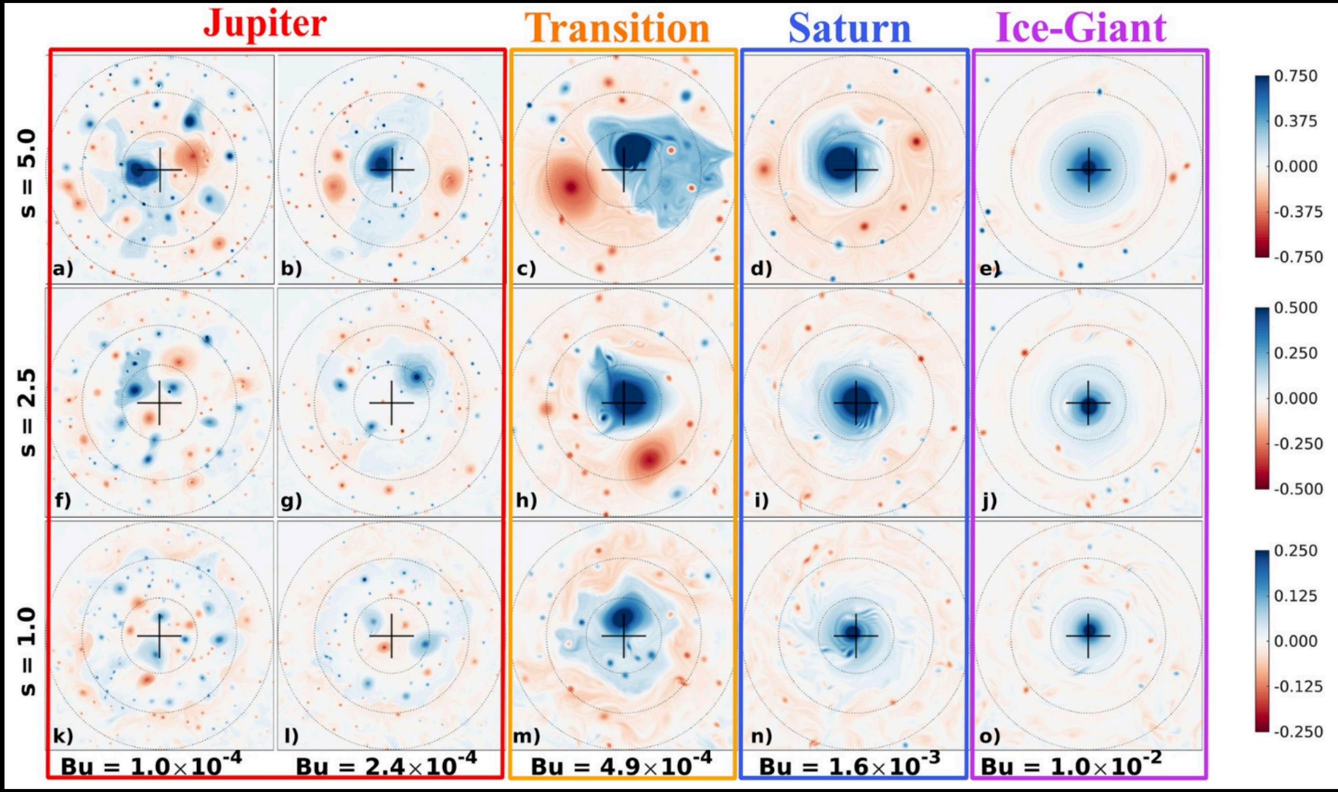


Cho and Polvani (1996)

Open questions

Polar cyclones on giant planets

- Shallow-water modelsof giant planets have circumpolar cyclones (e.g. Cho and Polvani, 1996), but so far none have resulted in vortex-crystal-like constellations
- Brueshaber et al. have produced a parameter analysis showing polar cyclones on giant planets are controlled by Burger number (i.e. oscillation frequency, atm. scale height, rotation rate, planetary radius)



$$\mathrm{Bu} = \left(\frac{NH}{\Omega L}\right)^2$$

Brueshaber et al. (2019)

Questions?

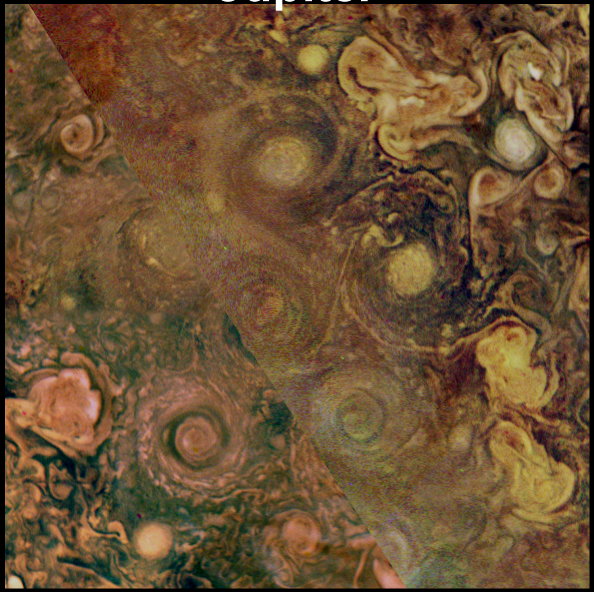
PJ17 Perijove Pass

Dynamical questions

Structure and stability

- Structure and stability
  - Vortex structure is mostly stable from PJ1 through 8
    - Why don't vortices merge?

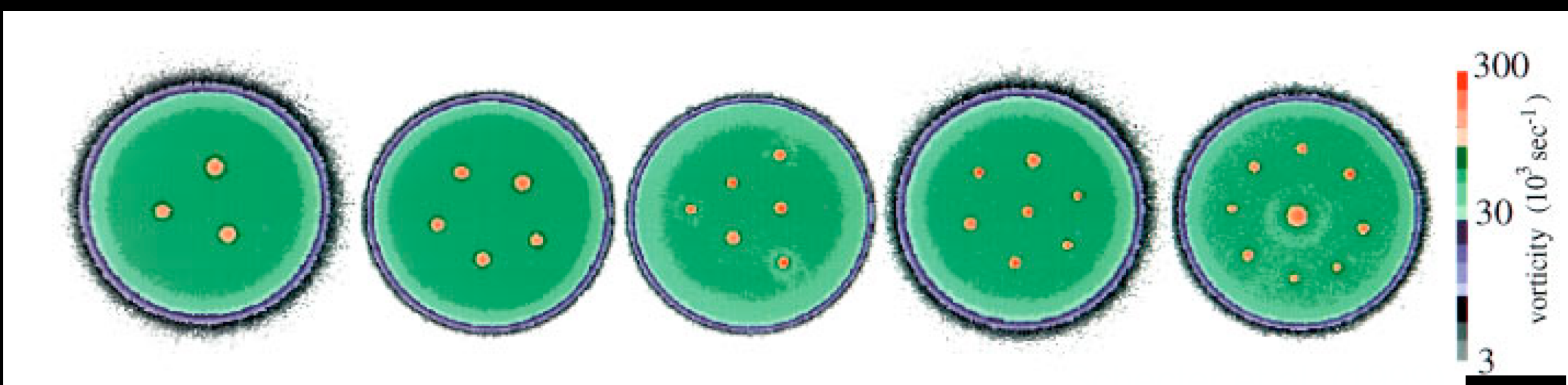
Jupiter



Dynamical questions

Structure and stability

- Structure and stability
  - Vortex structure is stable from PJ1 through 8
    - Why don’t vortices merge?
  - Vortex crystals (Fine et al. 1995, Schecter et al. 1999)
    - Observed in magnetized plasma columns and rotating superfluids
    - Described by 2D Euler equations



Dynamical questions

Depth of vortices

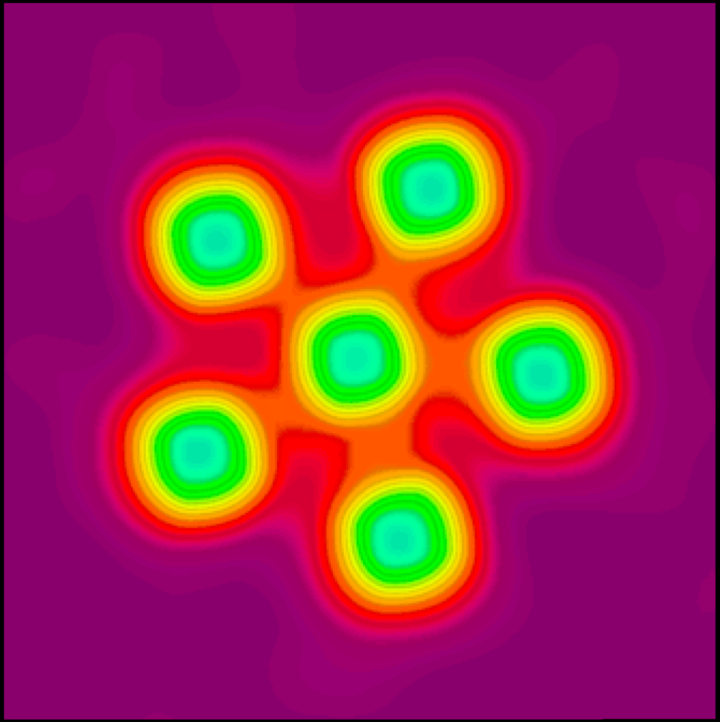
- Cyclone radius is ~1800 - 2800 km
- At least twice as large as Rossby deformation radius at poles, estimated as r_R<1000 km (Read et al. 2006)
  - Consistent with 2D fluid
    - Either shallow
    - or deep coherent columns

- 2D shallow-water models (Cho and Polvani 1995; O’Neill et al. 2015) can reproduce the transition region between mid-latitude jets and more turbulent polar regions fairly well.
  - And can produce cyclones near the poles
  - No vortex crystals modelled in atmospheres yet

Dynamical questions

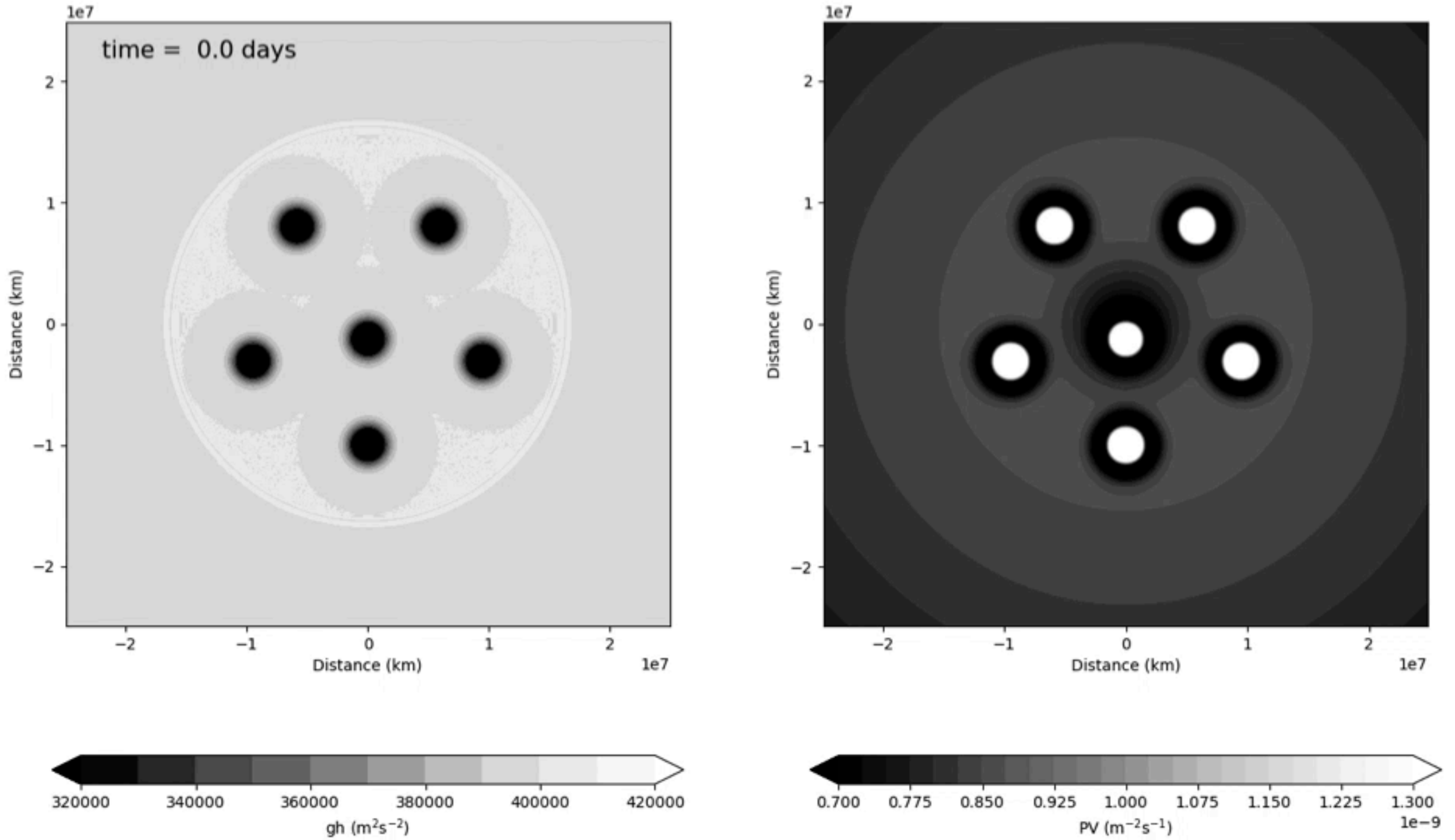
Structure and stability

- Structure and stability
  - Vortex structure is stable from PJ1 through 8
    - Why don't vortices merge?
  - Vortex crystals (Fine et al. 1995, Schecter et al. 1999)
- Shallow water model experiments
  - Vortices as initial condition →
  - explore under which conditions vortex structure remains stable



Dynamical questions

Structure and stability

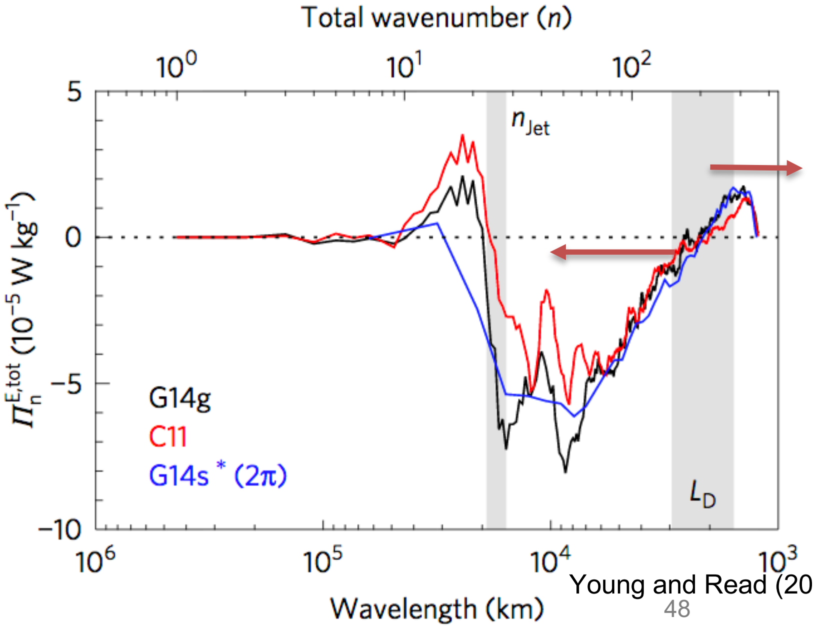


Harrinton, Li, Ingersoll in prep

Dynamical questions

Turbulence

- Vortex formation
  - Poleward transport of turbulent energy?
  - or inverse energy cascade from small scales?
- Turbulence in mid-latitudes (Young and Read, 2017)
  - Spectral flux analysis of velocity field from Cassini images
    - Atmosphere is energized at Rossby deformation radius, possibly via baroclinic instability
    - From there, upscale inverse kinetic energy cascade to global scale and <u>downscale kinetic energy cascade to smaller scales</u>

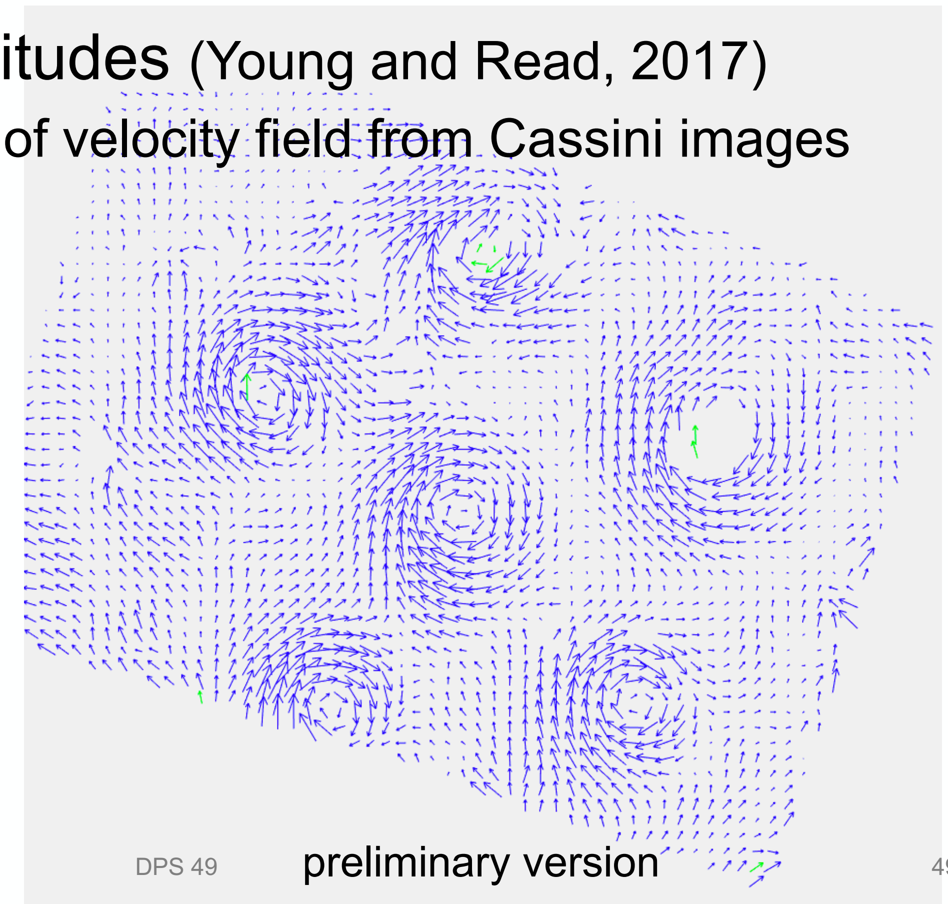


Young and Read (2017)

Dynamical questions

Turbulence

- Vortex formation
  - Poleward transport of turbulent energy?
  - or inverse energy cascade from small scales?
- Turbulence in mid-latitudes (Young and Read, 2017)
  - Spectral flux analysis of velocity field from Cassini images
- use this method on polar velocity fields from JIRAM data →



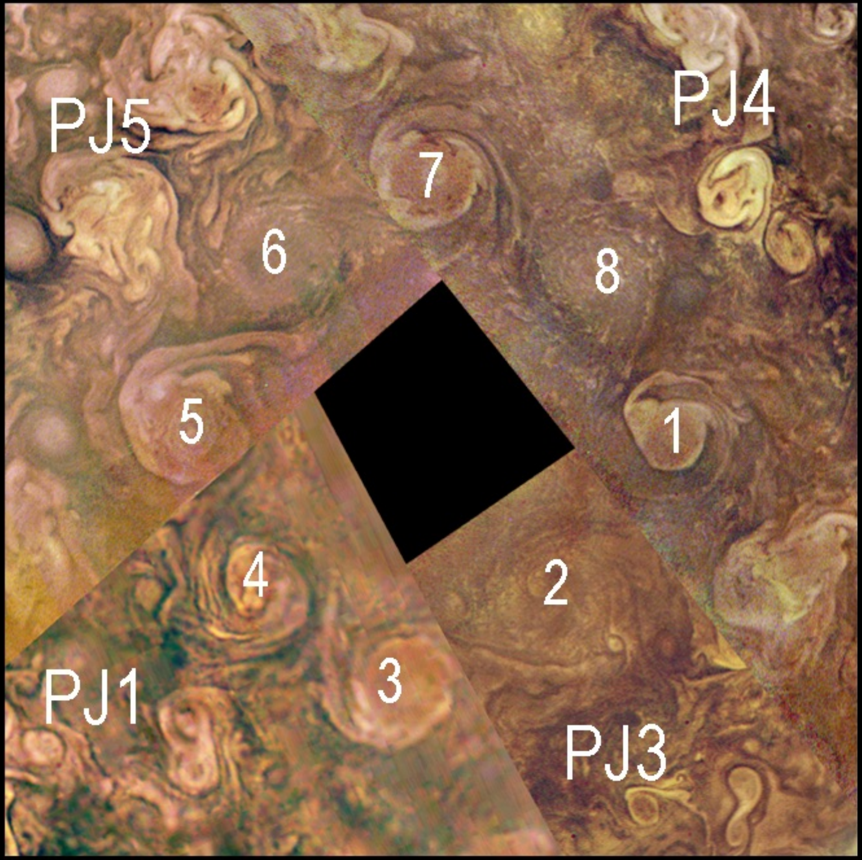
preliminary version

Dynamical Questions

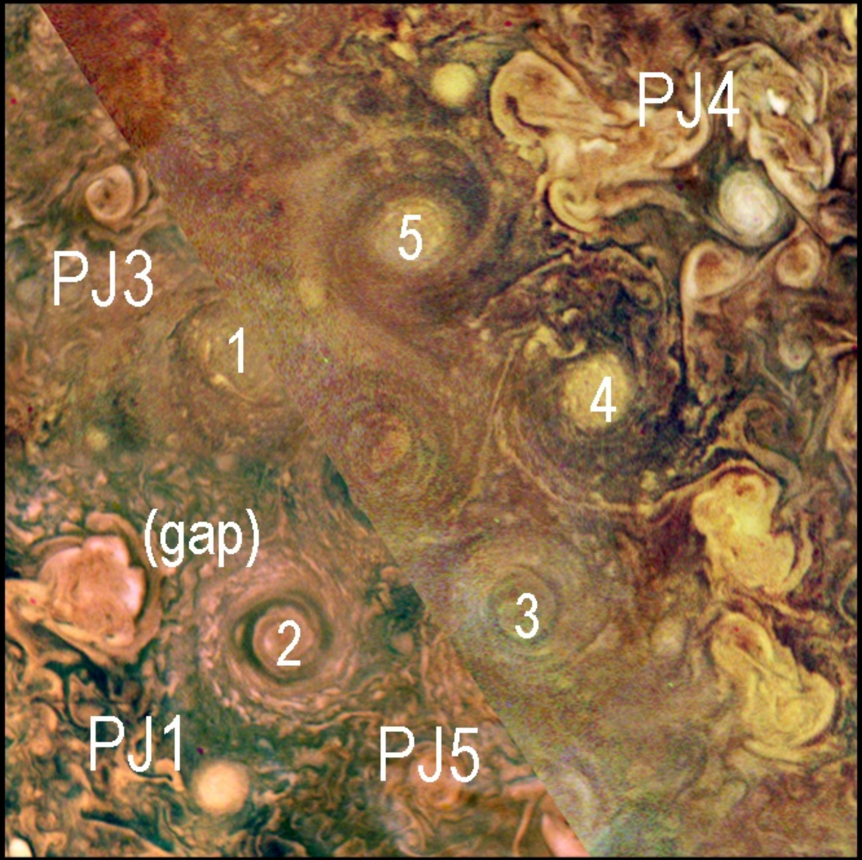
Hemispheric Dichotomy

- Can we identify the parameters that control the difference between north and south pole?

North Pole



South Pole



Future Work

- From JunoCAM observations
  - Continue mapping the long-term movement of the CPCs
- Using shallow-water and general circulation models:
  - Explore under which conditions vortex crystals appear at Jovian poles
  - Analyze energy fluxes of turbulence
    - During formation and maintenance phase
- Using velocity field measurements
  - Analyze turbulent energy spectra and fluxes from polar velocity field measurements

Polar Observations with Juno

Summary

- Composite images from different PJs
- Outer cyclones do not revolve around the pole, instead they “wobble” back and forth in longitude
- Central cyclone slightly changes distance to South Pole between PJs
- 5-point outer structure appear to be centered about the central cyclone rather than the rotational pole
- Overall the structure is stable enough to produce a composite image.

South Pole